1987

Target-directed Locomotion: A Critique Of The Short-term Memory For Spatial Locations Proposed By Thomson

Runa Elizabeth Steenhuis

CANADIAN THESES

THÈSES CANADIENNES

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30.

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30.

THIS DISSERTATION HAS BEEN MICROFILMED EXACTLY AS RECEIVED

LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVONS REÇUE

TARGET-DIRECTED LOCOMOTION:
A CRITIQUE OF THE SHORT-TERM MEMORY FOR SPATIAL LOCATIONS PROPOSED BY THOMSON

by

Runa E. Steenhuis

Department of Psychology

Submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

Faculty of Graduate Studies
The University of Western Ontario
London, Ontario
June 1987

ISBN 0-315-36587-0

THE UNIVERSITY OF WESTERN ONTARIO
FACULTY OF GRADUATE STUDIES

CERTIFICATE OF EXAMINATION

Chief Advisor

Examining Board

Advisory Committee

The thesis by
Runa E. Steenhuis

entitled
Target-directed locomotion:
A critique of the short-term memory for spatial locations
proposed by Thomson

is accepted in partial fulfilment of the
requirements for the degree of
Doctor of Philosophy

Date June 5/1987

Chairman of Examining Board

ABSTRACT

This thesis presents a systematic examination of a common visuomotor behavior -- locomotion directed to a target in the immediate environment.

The first part of the thesis focusses on an attempt to replicate an earlier finding of a highly accurate transitory short-term memory for target locations (Thomson, 1980, 1983). No evidence of such an accurate short-term memory was found here. The distance to the target, not the elapsed time, affected accuracy of walks with eyes closed. Delays of 2 and 4 s between viewing the target and walking did not result in a deterioration of performance. A 30 s delay did result in less accurate performance, however. Thus, a slowly decaying short-term memory was demonstrated.

The second part of the thesis examined the role of visual context in the control of locomotor accuracy. Being able to see the target led to highly accurate locomotion. Performance was less accurate when subjects had feedback of the area surrounding the target, but not of the target itself. Performance was less accurate still when subjects walked with eyes closed and least accurate when they walked in the direction opposite to the target. Target distance related to locomotor accuracy in a systematic way. Namely, as target distance increased so did locomotor errors. Absolute and variable errors showed a linear increase with increased target distance. Constant errors of underestimation frequently occurred when subjects walked toward the target, but errors of overestimation occurred when subjects walked in direction opposite to the target.

The next part of the thesis compares performance on the

target-directed locomotion task to performance on a second task in which subjects were asked simply to estimate the distance to the target, and to performance on standard written tests of spatial ability. Performance on the perceptual and locomotor tasks was related. Spatial ability related to perceptual performance, but not to locomotor performance. The last part of the thesis examines individual differences in locomotor accuracy. Males were more accurate than females when asked to walk to a nearby target with their eyes closed.

While the present thesis has only begun to examine all the perceptual processes, mo skills, and cognitive abilities involved in the control of target-directed locomotion, it is clear from the findings reported here that control of this apparently simple behavior is quite complex.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my thesis advisor, Dr. M.A. Goodale, for his guidance during the research and preparation of this thesis. He encouraged me to work independently, but was always ready to advise and help when I needed it. I especially appreciate the time and effort he put into helping me improve my writing style.

I would like to thank the members of my advisory committee, Dr. B. Timney and Dr. K.P. Ossenkopp, and the members of my examining board, Dr. P. Cain and Dr. K. Humphrey, for their valuable comments and suggestions. I would also like to thank Dr. M.P. Bryden who continued to have faith that the thesis would be completed.

I am indebted to Lynn Booth for her assistance with collecting some data when I injured my back. She well knows what it means to run subjects on the locomotion task.

I am grateful to my colleague and friend Ricki Ladowsky (Brooks) who helped me in so many ways. My years in the Clinical Neuropsychology program would not have been the same without her.

Finally, and most importantly, I would like to express my appreciation to my husband Paul, and my children Patricia and Jan for their support and understanding, even at the times when I know that it must have been difficult for them to understand.

This thesis is dedicated to my mother -- a very special person.

TABLE OF CONTENTS

TABLE OF CONTENTS CON'T

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES CON'T

LIST OF FIGURES CON'T

LIST OF FIGURES CON'T

LIST OF APPENDICES

Appendix Page

GENERAL INTRODUCTION

In our daily lives, we spend much of the time moving through space. In order to move about successfully, we must 'know' where we are and where we are going. Therefore, we must have information about the layout of the environment, about the position and movement of the whole body relative to the external environment, and about the position of the body parts relative to the body itself (Lee, 1978; Lee & Lishman, 1977). For movements toward near targets, all our senses may contribute to determining our position in space (Grüsser, 1982a, 1982b). Over longer distances, however, vision provides the richest source of information about position and movement (Grüsser, 1982a, 1982b; Jansson, 1983; Lee, 1978; Lee & Lishman, 1977).

It is easy to walk directly to a target that we can see. Vision allows both perception of the target location and feedback about locomotor accuracy. If the target is not in view, then we must determine how to reach it using previous knowledge. In other words, we must find out how to reach the target by using information we remember about the specific location of the target and/or what we know about the layout of the environment. Thus, walking toward a target that has recently gone out of view can be considered a visuospatial memory task, as well as a visuomotor task. It can be argued, therefore, that performance accuracy for targets that have gone out of view should be affected by errors in perceiving the initial position of the target, errors in executing the movement, and errors in storing and retrieving information about the position of the target.

The largest part of this thesis consists of a detailed examination of one particular approach to the problem of target-directed locomotion -- that of J. A. Thomson (1980, 1983). The fact that the work of this investigator is highly cited is testament in part to the paucity of empirical studies on this subject. As will become apparent, few other investigators have looked at visually guided locomotion and as a consequence, in reviewing the literature, I have had to examine a wide range of different research areas to gather relevant material. As was suggested above, locomotion with eyes closed toward a nearby target involves processes that are typically studied by workers in perception, motor skills, and cognition. In the following pages, I examine the way in which research from each of these areas contributes to our understanding of the visual control of locomotion.

VISUOSPATIAL AND VISUOMOTOR BEHAVIOR

The relation between perception and movement

Although a link between perception and movement was recognized in the past, visual perception and motor behavior have remained distinct areas of experimental investigation and theory development (Michaels & Carello, 1981; Turvey, 1977). Even though some theorists have attempted to stimulate an interest in the relationship between perception and action (Gibson, 1958, 1979; Kelso, 1982; Fitch, Tuller, & Turvey, 1982; Michaels & Carello, 1981; Turvey, 1977), in practice, few investigators have related evidence from perceptual experiments to evidence obtained in motor experiments (see Laabs, 1979; Laabs & Simmons, 1981 for notable exceptions). Recently, however,

consideration of the perception/action relationship has resulted in an increasing number of experiments examining the role of vision in motor behavior.

It is clear that motor behaviors like locomotion are not completely dependent on vision, since the blind can walk around in the environment (Jansson, 1983; Strelow, 1985). Vision, however, has been shown to play the primary role in the control of a number of different aspects of locomotion in sighted humans (Gibson, 1958, 1979; Lishman & Lee, 1973; Strelow & Brabyn, 1981). For example, vision provides the only accurate source of displacement information when one is moving with or against an unusual force, such as the wind or a water current. In this situation, proprioceptive feedback about limb movement does not give accurate information about actual displacement.

Lishman and Lee (1973) provided an experimental demonstration of the dominant role that vision plays in the control of the sense of self-movement. These investigators demonstrated that when visual and mechanical/vestibular kinesthetic information conflicted, information from the visual system prevailed. Subjects stood on a trolley in a movable room. When the trolley and the room moved in the same direction, subjects with their eyes closed said they were moving. Feedback from the vestibular system and from the ankle joints was thought to be the source of the self-movement sense. When subjects opened their eyes they claimed they were stationary, even though the room and trolley were still moving. This altered perception indicated that the vestibular/mechanical feedback, which would have continued to indicate movement, was ignored or was overruled by visual cues. In

addition, subjects standing with their eyes open on a stationary trolley in a moving room stated they were moving, even though vestibular/mechanical feedback would have indicated they were stationary. The dominance of visual feedback or visual kinesthesis, as Lee and his colleagues (Lishman & Lee, 1973) refer to it, was persuasive even for the experimenters themselves. Vision has also been demonstrated to exert control over other aspects of locomotion including stopping (Lee, 1976; Lee & Lishman, 1977; Schiff & Detwiler, 1979) and steering (Lee & Lishman, 1977).

Following the initial demonstrations of the dominant role vision plays in the control of many motor behaviors, a number of investigators began to look more closely at the nature of that control. Experimental evidence has indicated that many motor acts, once initiated under visual control, can proceed without visual feedback until the last few seconds (Schiff & Dewiler, 1979) or milliseconds (von Hofsten & Lee, 1982) before termination. Such results have led to the suggestion that visual feedback is obtained and/or used in a discontinuous manner (see Lee, 1978; Lee & Thomson, 1982; Thomson, 1980, 1983). Lee (1978), for example, demonstrated that skilled long-jumpers visually adjusted their pace length on the last few strides before they reached the takeoff platform. Visual feedback available over the initial segment of the run-up did not affect pace length.

Further support for the notion of discontinuous visual feedback comes from evidence of a highly accurate short-term memory for target positions. Thomson (1980, 1983) found that locomotion with eyes closed towards targets up to 21 m away remained as accurate as if full visual

feedback was available provided the target was reached within 8 s of last viewing. Thomson used these results to argue that locomotion can proceed for about 8 s before a target would need to be sampled again. Thus, the visual system would be free to sample other targets. The details of this interesting hypothesis and its empirical support will be examined in deta later in the thesis.

But while it is clear that visual cues are a powerful source of control in many different motor behaviors, the question remains as to what information from the rich array available in the environment is used in that control. Because animals perceive and behave in the environment, we must also consider the environment in which perception and action take place (Gibson, 1979; Droogleever Fortuyn, 1982).

Perception and the environment: The role of optic flow

Psychologists interested in perception have typically paid little attention to the actual environment in which perception normally takes place (Gibson, 1966, 1979; Michaels and Carello, 1981; von Hofsten & Lee, 1982). Classically, visual perception has been studied in laboratory settings using psychophysical methods (Gibson, 1979). The focus of perceptual research was on pattern and form recognition using two-dimensional stimuli and restricted viewing conditions (limiting the movement of the head and/or eyes). Since visual perception was thought to be the process of reconstructing the three-dimensional environment through a series of snap-shot like retinal images (Vicker, 1979), these conditions were thought to simulate normal viewing in all important respects. An interest in the very basic problems of how animals locomote in the environment, avoid obstacles and catch prey led Gibson

(1958, 1979) to propose an alternative ecological approach to the study of visual perception. Gibson's ecological psychology recognized the mutual relationship between an animal and its surroundings (see Gibson, 1979 for a detailed account of the theory).

Gibson (1966, 1979) developed his controversial theory of visual perception based on a detailed account of 'information' directly available in the "optic array" (for criticisms of the theory see Hamlyn, 1977; Heil, 1981; and Neisser, 1977). The optic array is created by the static and dynamic arrangement of the environment. Movement in the environment, including that of the "perceiver/actor" (Gibson, 1979), is responsible for optic flow. For example, as one drives along a road that extends towards the horizon, the road, the trees, and the clouds appear to expand as one moves forward. The rate of this expansion across the retina has been shown to be directly related to the speed of movement. The point of expansion of the optic flow is thought to change as the direction of movement changes. Generally, self movement and movement of objects within the environment induce distinctive flow patterns and, therefore, can be differentiated (see Gibson, 1979 for a complete discussion of optic flow).

Optic flow has been implicated in the control of locomotion (Gibson, 1958, 1979). While Gibson's (1958, 1979) original account was largely theoretical and others have extended these arguments (Lee, 1974; Lee & Lishman, 1977; Lee & Thomson, 1982; Strelow, 1985), there is some experimental evidence to suggest that optic flow is important in the guidance of locomotion (Johansson, 1977; Regan & Beverley, 1979; Schiff & Dewiler, 1979). There is not, however, total agreement on the

specifics of this control (Llewellyn, 1971).

Recently, Strelow and Brabyn (1981) carried out an empirical test of Gibson's (1958) postulations regarding the perceptual stimuli sufficient for the visual guidance of locomotion. They manipulated the availability of background and foreground information and measured locomotor accuracy. Subjects were required to walk alongside of 6 poles that were arranged vertically in the middle of a large darkened room. The poles, which were marked with fluorescent paint and spaced 2 m apart, provided foreground information when illuminated by an ultraviolet lamp. Background information was provided by 14 LEDs positioned at 2 m intervals along two adjacent walls of the experimental room or by leaving the room lights on. When background information was eliminated, thereby reducing the cues available from motion parallax and the possibility for subjects to choose an aiming point, deviations from a straight path increased over conditions where subjects walked with the room lights on. Errors also increased over a condition where some background information (the 14 LEDs) was available. The addition of an aiming point, in the absence of other background information, was also found to assist performance. These investigators suggest that:

> General textual flow appears to assist guidance, but a defined aiming point adds some additional precision. When this is applied to conditions of normal perception, it follows that locomotion may be performed with the use of a number of control strategies with different perceptual information being selected in accordance with the nature of

the task and the environmental setting. (p 197)

According to Gibson (1979), the visual system is not separate from the motor system, nor is the animal separate from its environment. The goal of the visuomotor system is action, not just movement or perception. Locomotion directed toward objects in the environment is just such an action. However, there is very little direct evidence about how factors such as target distance and elapsed time affect locomotor accuracy for such targets. In spite of differences in theoretical orientation and experimental methodology, some insight into the potential for accurate performance may be gained from independent evidence regarding perceptual accuracy and motor accuracy.

The effect of target distance

Perceptual accuracy and target distance. Attempts to examine the 'metric' of visual space have produced conflicting results (see Baird, 1970; Gilinsky, 1951; Wagner, 1985). Recently, Wagner (1985) used a number of different psychophysical methods to determine the properties of visual space. Judgments of distances, angles, and areas were examined in a large open field under free viewing conditions. Wagner found that although visual space is basically Euclidean, it is not the same as physical space. According to Wagner (1985), "Visual space is compressed in the in-depth dimension when compared with physical space (at least within the range 5-70 m from the observer)" (p 489). He suggested that the conflicting results reported in the perceptual literature most probably reflect differences in the way in which the subject's view of the stimuli was restricted. He concluded that no single description of visual space will be sufficient, because as

experimental conditions change so do the properties of subjective visual space. For this reason and because the experiments described in this thesis, like Wagner's, also used free viewing conditions, the remainder of this section deals only with those studies that used free viewing conditions and more naturalistic settings.

Gibson and Bergman (1954) found that perceptual errors in estimation of the distance to targets between 52 and 395 yards away in an open field were a constant proportion of target distance. For each of 18 targets placed in a random array in the field, subjects were simply asked to state the number of yards they thought it was to the target. The results of this work suggested there was a linear increase in perceptual errors with increased target distance. Similarly, Harway (1963) reported that constant errors increased linearly with successively greater distance estimations. In Harway's task, a marker was pulled over the ground until the subject indicated that the distance the marker had moved from its previous position was equal to the length of a 1 foot standard rule placed on the ground in front of him/her. As the distance between the subject and the marker increased with successive estimations, so did the interval the marker was moved before the subject indicated that it was equal to 1 foot. This overestimation of the distance the marker should be moved is consistent with the underestimation of 'real' distance found by others (see Wagner, 1985). Some investigators have suggested errors in perception increase in a non-linear fashion, but do not agree as to the precise function (Gilinsky, 1951; Kunnapas, 1960). The relation between subjectively estimated distance and actual physical distance may depend

on environmental and experimental variables (Kunnapas, 1960; Sadalla & Magel, 1980; Wagner, 1985).

There is abundant evidence that subjective judgments of sensory magnitude, including distance estimates, are subject to biases (see Poulton, 1979 for a review). For example, Weber's Law indicates errors in judging changes in sensory amplitude are related in a constant way to the size of the stimulus. Another such effect, noted for a wide variety of sensory stimuli, is the tendency for subjects to overestimate the size of small stimuli and underestimate the size of large stimuli. This so-called "range effect" (Searle & Taylor, 1948; Slack, 1953) is not only limited to sensory stimuli, but has been noted in a wide variety of cognitive and motor performances (Poulton, 1975). One of the first reports of range effects was made by Fullerton and Cattell (1882 cited by both Woodworth, 1899 and Hollingworth, 1909) who examined the accuracy of motor behavior in relation to movement extent.

Motor accuracy and target distance. The accuracy of motor behavior was addressed by a number of early investigators (Hollingworth, 1909; Woodworth, 1899). Very small errors were noted on skilled visually guided movements such as writing (Woodworth, 1899). Woodworth presented a comprehensive examination of accuracy in discrete limb movements. He noted a reciprocal relation between speed and accuracy for movements made with eyes open, but not for movements made with eyes closed. As movement amplitude increased, accuracy decreased for limb movements executed without visual feedback.

Woodworth's (1899) findings have been confirmed by subsequent investigations. The relation between movement extent, movement time, and accuracy for visually guided movements was formalized by Fitts (1954) who demonstrated that the time taken to complete an accurate movement depended on target distance and target size. Fitts' Law (Keele, 1968), as this relationship became known, does not hold for non-visually guided movements since accuracy cannot be maintained in the absence of visual feedback. As Woodworth (1899) noted, a reciprocal relation exists between distance and accuracy of non-visually guided limb movements. Accuracy decreases as distance increases. More recently, Posner (1967) has reported that absolute errors in reproducing non-visually guided limb movements also increase with the extent of the movement.

Later investigators found, just as Woodworth (1899) had, that constant and variable errors were affected differently by target distance when a movement was made with eyes closed (see Howarth & Beggs, 1981 for a review). Woodworth found that constant errors varied as a function of distance in a way that would be expected by the "range effect". Variable errors, on the other hand, have been reported to increase approximately as a square root of distance (Woodworth, 1899) or in direct proportion to distance (Fitts, 1954). Distance was not the only variable to affect performance of non-visually guided limb movements. The length of time the subject waited between the stimulus movement and the response movement was also found to increase errors (Woodworth, 1899).

The early finding of Woodworth (1899), that delays affect the accuracy of non-visually guided movements, was not followed up until the 1960s. Laabs and Simmons (1981) in their review of motor memory attribute the emergence of work in this area to the demonstration by Peterson and Peterson (1959) of a short-term memory for verbal material. Studies on motor memory primarily involve the repetition of limb movements after a delay. A number of consistent findings have emerged from these investigations. Empty intervals of 3 s or more between the initial movement and its later reproduction have been associated with an increase in the underestimation of the movement amplitude. This increase in underestimation can occur in combination with the already reported range effects when movement distance is also varied. Variable errors increase as a function of both the length of the delay and the amplitude of the required movement.

Cognitive representations of space

Cognitive psychologists, too, are interested in memory. However, they are less concerned with the precise replication of a particular movement than they are with the way in which we remember the layout of the environment through which we have moved. Since the early work of Piaget and Inhelder (1956), cognitive psychologists have made a distinction between the ability to act in the environment (sensorimotor behavior) and the ability to form conceptions of how the environment is laid out (spatial representations). Most research in this area has focussed on representations of what is often called 'large-scale space' (Liben, Patterson, & Newcombe, 1981; Pick & Acredolo, 1980), the parts

of the environment that cannot be viewed from a single vantage point (Siegel, 1981). Mental representations of large-scale space have been assessed using a variety of measures including verbal reports, map drawings, and model constructions. The ability to produce maps and models is often assumed to indicate both knowledge about spatial relations as well as competence to move through the environment represented by those maps and models (Liben, 1981). Many cognitive psychologists have stressed the importance of assessing mental representations of the environment while at the same time ignoring the need of assessing performance in the environment. While the role of visuomotor behaviors in the formation of spatial representations has not concerned most cognitive psychologists, others argue that sensorimotor behaviors, such as reaching, grasping, and walking, are a necessary precursor to the formation of spatial representations (see Hart & Moore, 1971).

However, performance in large-scale space was rarely examined directly. Recently, the relation between representations of space and performance in space has been questioned. In children (Down & Siegel, 1981; Siegel, 1981) and in the blind (Strelow, 1985), performance in the environment is better than would be expected on the basis of their ability to draw maps and make models of space. This would suggest that maps and models may not be an adequate means of assessing the internal spatial knowledge that people use to guide their movements through familiar environments. This apparent dissociation has led some investigators to question the assumption that spatial behaviors use the kinds of spatial representations revealed by maps, models, and verbal

reports (Acredolo, 1981; Newcombe, 1981).

While most cognitive psychologists believe that finding one's way in large-scale environments depends on "cognitive maps" (after Tolman, 1948), they have failed to consider the possibility that spatial representations could also play a role in the control of locomotion toward a visible target. When a target is visible, it has always been assumed that locomotion is controlled directly by vision and not by mental representations at all. Indeed, internal representations of 'small-scale space', the parts of the environment that can be viewed from one vantage point (Siegel, 1981), have not been of concern to most cognitive psychologists. Evidence of memory for target locations in small-scale space, or what I will call the immediate environment, is limited to a few isolated publications (Corlett, Patla, & Williams, 1985; Elliott, 1986; Thomson, 1980, 1983).

THE PRESENT INVESTIGATIONS: OBJECTIVES

It was the evidence presented by Thomson (1981, 1983), that locomotion directed to a target in the immediate environment could proceed for up to 8 s without visual feedback, that provided the impetus for the present thesis. Originally, I had planned to test patients with unilateral brain damage on Thomson's short-term memory task. The thesis took another direction, however, when I was unable to replicate Thomson's original finding. My unsuccessful attempts to find any evidence of an 8 s short-term memory (chapter 1) led to a more detailed examination of the role of visual feedback in the control of locomotor performance (chapter 2). It became clear very early in these

investigations that there were significant individual differences in the ability to walk with eyes closed to a target in the immediate environment. These differences are examined in the final two chapters. In chapter 3, an attempt was made to relate locomotor accuracy to both perceptual accuracy and spatial ability. In chapter 4, I looked at how locomotor accuracy was related to a number of other variables including sex, height, pace length, and walking speed.

CHAPTER 1

SHORT-TERM MEMORY FOR A TARGET LOCATION IN THE IMMEDIATE ENVIRONMENT

Most animals, including human beings, are able to perform a number of complex visually guided movements simultaneously. A hunting animal, for example, is able to avoid obstacles in the environment while at the same time stalking or pursuing prey. Thomson (1980, 1983) has argued that the need to divide attention between different parts of the environment would require a system that allows sampling of visual information rather than one that demands continuous visual feedback. According to Thomson, the intermittent sampling would be supported by an accurate short-term memory for different target locations.

In a series of recent experiments, Thomson (1980, 1983) has shown that accurate locomotion in humans might normally involve such a system. In one experiment, subjects were required to walk with their eyes open or closed to a small target placed on the ground at different distances up to 21 m away. With their eyes open, as one might expect, the subjects were very accurate at all distances. All mean signed errors varied around the target. Generally, individual subjects walked to the same location on different trials at a given distance (low intrasubject variance). In addition, different subjects walked to similar locations relative to the target (low intersubject variance). What was surprising was that subjects were equally accurate with their eyes closed when the targets were 9 m or less away. At 12 m, their performance suddenly became much more variable. Mean signed errors still varied around the target, but the standard deviation of these signed errors showed an abrupt and approximately 5-fold increase.

Thomson used the standard deviation of signed errors as a measure of performance variability and, therefore, did not differentiate between intersubject and intrasubject sources of variance. Problems associated with combining sources of variance will be discussed later and have been outlined elsewhere (Elliott, 1986).

By introducing a delay between viewing the target and walking, Thomson was able to show in a subsequent experiment that the sudden increase in variability at 12 m was due to the passage of time rather than the distance that subjects were required to walk. In other words, the longer the delay, the closer the target at which the breakdown in accurate performance occurred. Conversely, when subjects were asked to run rather than walk toward the target with their eyes closed, they could often continue to perform accurately even with targets as far away as 21 m. In fact, provided the subjects reached the target within 8 s of viewing, their performance with their eyes closed differed very little from their performance with their eyes open. On the basis of these results, Thomson postulated that subjects were making use of a memory for the location of the target that decayed very rapidly after 8 s. During normal visually guided locomotion, therefore, subjects would be required to update the location of a target at least every 8 s, and would be free to use their visual system to sample other information within the environment.

A number of investigators, in addition to Thomson, have found evidence of memory for visuospatial information. In contrast to Thomson, these other investigators have focussed their attention, not on short-term memory for the distance of a particular target, but on

memory for the spatial layout of the environment (in animals see for example, Menzel, Premack, & Woodruff, 1978; O'Keefe & Nadel, 1978; Olton, 1977). Most of the studies of spatial memory, in humans, involve route-finding behavior (see Liben, 1981; and Pick & Acredolo, 1980) in the environment and in complex mazes (Lingberg & Garling, 1981a, 1981b, 1982). However, accurate replication of distance and the role of short-term memory has been the focus of investigations of kinesthesis (the sense of movement and position of the body from proprioceptive cues). When subjects were asked to reproduce the extent of a limb movement, absolute errors increased with distance (Posner, 1967) and with length of retention interval (Adams & Dijkstra, 1966). Short-term memory has also been found for visually presented targets. Memory for the location of a spot on a piece of paper has been shown to depend on the duration of the presentation and the retention intervals (Dale, 1973). Similarly, in a task where subjects aimed a stylus at a 1 cm target, accuracy decreased as a function of delay length (Holding, 1968). Independent evidence of short-term memory for movements and for target locations would appear to lend support to Thomson's claim that locomotor accuracy for visually presented target locations should deteriorate when delays are introduced between viewing the target and walking.

Since Thomson's (1980, 1983) original experiments, there have been no other demonstrations of a highly accurate short-term memory for target distance during locomotion. Recently, Elliott (1986) was unable to find any evidence to support Thomson's claim. Elliott, therefore, concluded continuous visual information was important in the control of

accurate locomotion. As will become apparent, like Elliott, I (also see Steenhuis & Goodale, 1986) failed to find any evidence that the accuracy of subjects walking toward a target with their eyes closed detcceriorated abruptly when the elasped time exceeded Thomson's critical time of 8 s. Elliott was unable to offer an explanation for his failure to replicate the short-term memory effect. An explanation will be given here. Moreover, it will be postulated that the type of visual feedback necessary to guide locomotion toward a target in the immediate environment, that is, discontinuous or continuous visual feedback, depends on the task demands.

In the present experiments, there has been an attempt to address some of the methodological issues that cloud the original interpretation put forward by Thomson (also see Elliott, 1986) and an attempt to offer an alternative account of locomotor control that stresses the role of target distance in determining the nature of that control. The first experiment compared accuracy of target-directed locomotion with and without vision. A replication of Thomson's results would have shown that provided a subject reached the target within 8 s, walks with eyes closed would be as accurate as those with eyes open.

The second experiment introduced delays of 2 and 4 s between viewing the target and walking, with the expectation that when walk-time and delay-time increased to more than 8 s, an abrupt deterioration in performance accuracy would be found. Experiments 1 and 2 duplicated Thomson's methodology, using the methodological details provided in his papers (see Experiments 1 and 2 of Thomson, 1983). The third experiment was conducted following discussions with

Thomson (1985). These discussions resulted in a number of changes to the experimental methodology (see Thomson, 1986 for criticisms of Elliott, 1986). The continued failure to find any evidence of a short-term memory of the type Thomson described led to a fourth experiment. In this final experiment, a very different type of short-term memory from the one proposed by Thomson was demonstrated.

EXPERIMENT 1

Method

Twenty right-handed volunteers (10 male and 10 female) with normal or corrected vision and ranging in age from 18 to 23 (mean = 19.05, s.d. = 1.09 years) walked to a target placed in an approximately 30 m long by 4 m wide corridor. A metal strip at one end of the hallway served as a start-line. The target was a 30 X 15 X 4 cm block of wood painted white. At the beginning of the experiment, subjects were given 5-10 minutes of practice walking with their eyes closed. They did not practice walking to any particular target or distance. Following the practice session, subjects were instructed to walk along a path to one side of the target and stop when they thought the front of their toes lined up with an imaginary line that extended from the front edge of the target. The experimenter, walking to the left of the subjects, accompanied them on all trials, to ensure that they did not walk into anything or open their eyes. On experimental trials, subjects walked both to and from the target with their eyes closed. They received no feedback about their performance until the end of the experiment. Between trials, subjects waited out of view

while the target was placed in position. The possible use of sound cues was minimized by having the subjects listen to white noise played through the headphones of a Sony-Walkman while they walked both to and from the target. This procedure was thought to be important since subjects may have been able to use echoes produced by their footfall to determine where they were in the hallway.

After viewing the target for 5 s, at the signal of the experimenter, subjects walked to a target placed at 3, 6, 9, 12, 15, 18, or 21 m. Five trials at each distance were presented randomly in each of two conditions. The entire task was performed with eyes closed first and after a short break was repeated with eyes open. When walking with eyes open, subjects were asked not to look down as they approached the target, but to stop abruptly when they thought their toes lined up with the imaginary line that extended from the front edge of the target.

All subjects were naive as to the purpose of the investigations. In this experiment, subjects were given credits for their participation as part of the requirements for an undergraduate Psychology course. Additional information was collected from most of the subjects in this and all following experiments about a number of other variables, including the subject's height, pace length, and walking speed. These data will be discussed in Chapter 4.

Data analysis

The distance walked and the time taken from closing the eyes until the subject stopped walking were recorded. The distance walked was obtained from a 30 m tape measure placed along one side of the

corridor. Errors were calculated by subtracting the distance walked from the distance to the target. Since the width of the hallway limited how far the subjects could veer away from a straight path, errors perpendicular to the direction of movement were not recorded. (Subjects seldom veered as they walked, especially for targets that were less than 12 m away. However, even if subjects had veered until they were touching the wall, the additional distance walked by the subject would have been only 8 cm on a 12 m walk.)

For each subject, signed errors (where negative scores indicated an undershoot and positive scores indicated an overshoot), constant errors (mean signed error over 5 repetitions), variable errors (the standard deviation of the signed error over 5 repetitions), and mean walk-times were calculated. Constant error and variable error measures were substituted for the signed errors and standard deviation of signed errors that Thomson used. The experiment was designed to examine differences between walks without visual feedback and walks with visual feedback. For each subject, performance with eyes closed was compared to performance with eyes open. Essentially, each subject acted as his/her own control. For this reason, constant errors and variable errors, which reflect intrasubject effects, were used in this and all following experiments.

The error scores were subjected to the appropriate repeated measures analyses of variance: The constant and variable error scores were each subjected to a 2 (condition) X 7 (distance) repeated measures analysis of variance. Significant effects were further evaluated by the use of post hoc tests of Least Significant Differences (LSD).

Where necessary, the degrees of freedom were adjusted using the Satterthwaite procedure (Kirk, 1968). The relation between variable error and distance was analyzed for linear, quadratic, and cubic components using a trend analysis. (A replication of Thomson's results would have shown both linear and cubic components for the relationship between variable error and target distance.)

Results

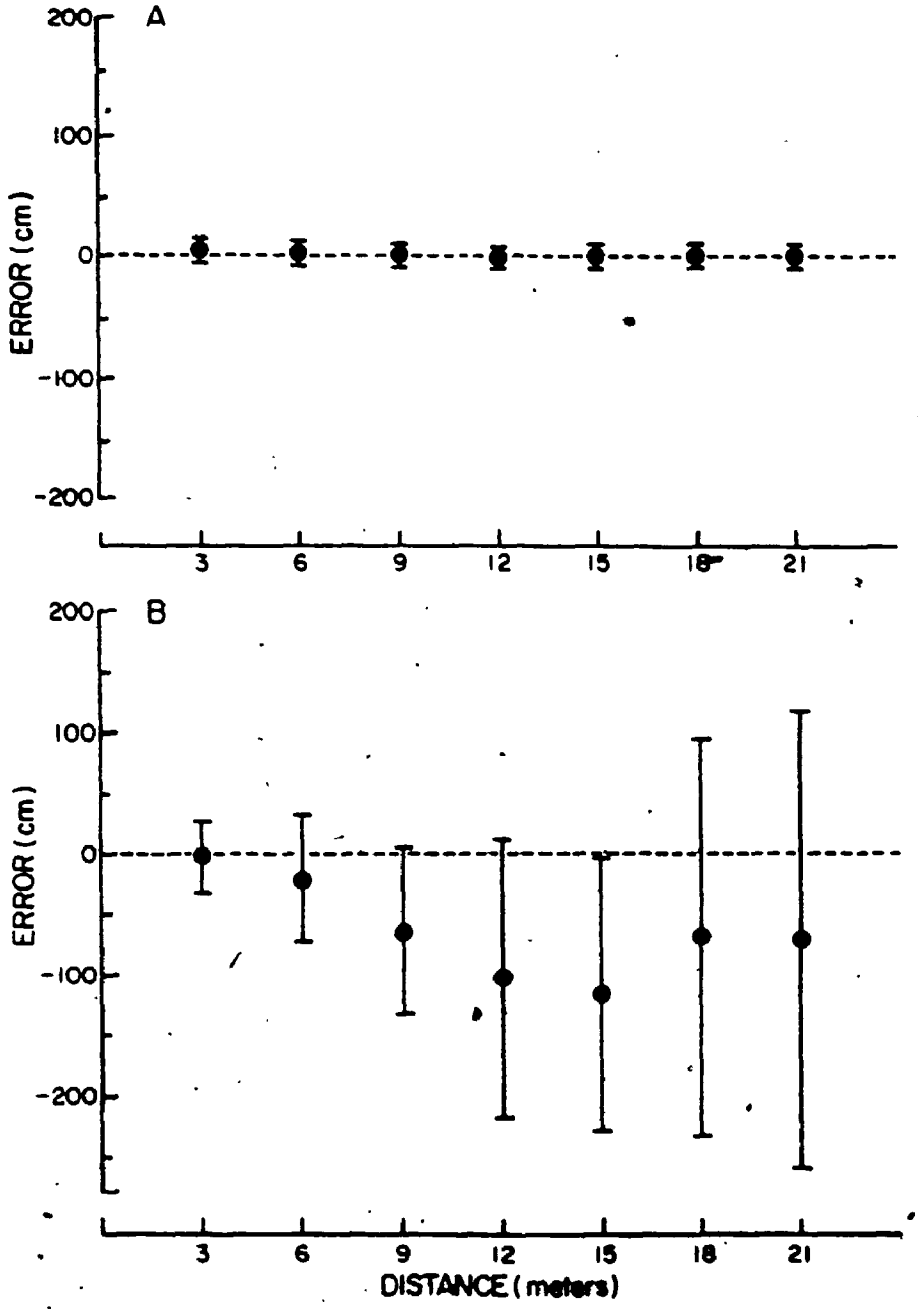
The effect of target distance

Constant error. With vision, performance was very accurate at all distances (see Figure 1a). The final position for all walks varied around the target. Without vision, however, (see Figure 1b), performance was much less accurate. As is clearly shown in Figure 1, the standard deviation of mean constant errors increased with distance on walks without vision, but not on walks with vision.

When subjects walked with eyes closed, they tended to undershoot the target (see Figure 1b; main effect of condition: $F(1,18) = 11.16$, $p < .005$). Undershoots increased with distance up to 15 m, then decreased slightly at 18 and 21 m (main effect of distance: $F(6,108) = 5.33$, $p < .0001$; distance by condition interaction: $F(6,108) = 5.17$, $p < .0005$). In comparison to performance with vision, undershoots on blind walks were significant (LSD: $df = 52$, $p < .05$) at all distances except 3 and 6 m ($p > .05$).

Variable error. Variable error increased with distance (main effect of distance: $F(6,114) = 18.29$, $p < .0001$), but only for walks with eyes closed (main effect of condition: $F(1,19) = 379.63$, $p < .0001$;

Figure 1. Mean constant errors and standard deviations (cm) for subjects (n = 20) walking with eyes open (A) and eyes closed (B) to target distances between 3 m and 21 m. For each subject, constant errors were calculated by averaging signed errors over 5 trials at each distance. The standard deviation of mean constant errors, therefore, reflects intersubject variance.


A
200
100
0
-100
-200
ERROR (cm)
3
6
9
12
15
18
21
B
200
100
0
-100
-200
ERROR (cm)
3
6
9
12
15
18
21
DISTANCE (meters)

condition by distance interaction: $F(6,114) = 18.00$, $p < .0001$). Trend analysis showed a highly significant linear relation between distance and variable error for walks with eyes closed (see Figure 2; $F(1,19) = 125.79$, $p < .0001$), but not for walks with eyes open ($F(1,19) = 3.45$, $p = .08$). Significant quadratic and cubic functions were not present in either condition. Differences between variable errors for walks with and without vision were significant (LSD: $df = 133$, $p < .001$) at all distances except 3 m ($p > .05$).

Effects of time

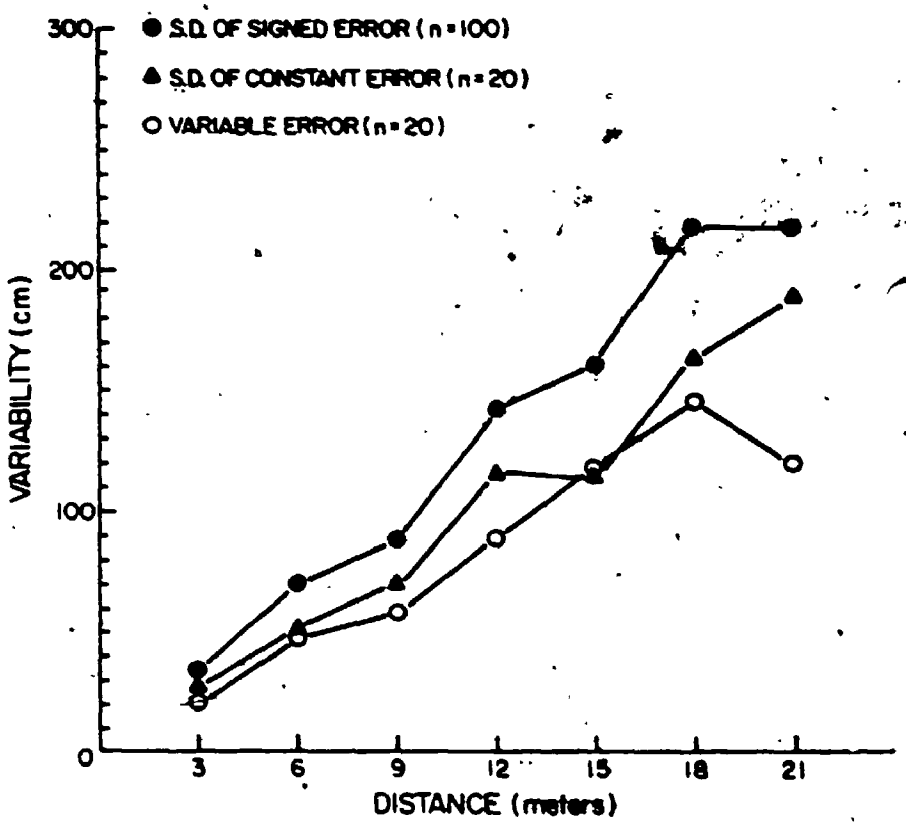
On average, subjects took longer than 8 s to reach the 9 m target whether or not they were walking with their eyes open or closed (Table 1). On the basis of Thomson's (1980, 1983) results, an abrupt increase in variable error and/or standard deviation of constant error would be expected at 9 m. Neither of these measures showed such an increase at 9 m (see Figure 2). Some walks at 9 m, however, took more than 8 s and some walks took less than 8 s. The same was true of walks to the 6 m target. The linear increase in performance variability, therefore, could have been due to a combination of walks that exceeded the critical time with walks that did not exceed it. Variability could have increased between the 6 and 9 m targets simply because a greater number of walks to the 9 m target took more than 8 s. An additional problem stemmed from the fact that Thomson (1980, 1983) had combined intrasubject and intersubject sources of variance when he assessed performance accuracy. For these reasons, the data were analyzed further. First, an analysis of the type Thomson used was performed. Second, time and distance effects were considered separately for all

Table 1

Mean times and standard deviations (s.d.) in seconds (s) for all walks with eyes open and eyes closed (n = 20)

	Distance (m)						
	3	6	9	12	15	18	21
Walk-time (s)	Eyes open						
(mean)	4.85	7.68	9.54	12.16	14.35	16.50	18.90
(s.d.)	0.69	1.13	1.49	2.11	2.34	2.39	2.89
	Eyes closed						
(mean)	5.01	7.61	9.97	12.44	15.11	18.39	20.77
(s.d.)	0.73	1.02	1.23	1.86	1.94	2.29	2.54

Figure 2. Measures of performance variability (cm) including standard deviations of signed errors (n = 100; 5 repetitions by 20 subjects; closed circles), standard deviations of constant errors (n = 20; closed triangles), and variable errors (n = 20; open circles) are shown with respect to target distance (m) for walks without vision.


S.D. OF SIGNED ERROR (n=100)
S.D. OF CONSTANT ERROR (n=20)
VARIABLE ERROR (n=20)
VARIABILITY (cm)
300
200
100
0
3
6
9
12
15
18
21
DISTANCE (meters)

walks to the 6 and 9 m targets. The results of these analyses are discussed in the following two sections.

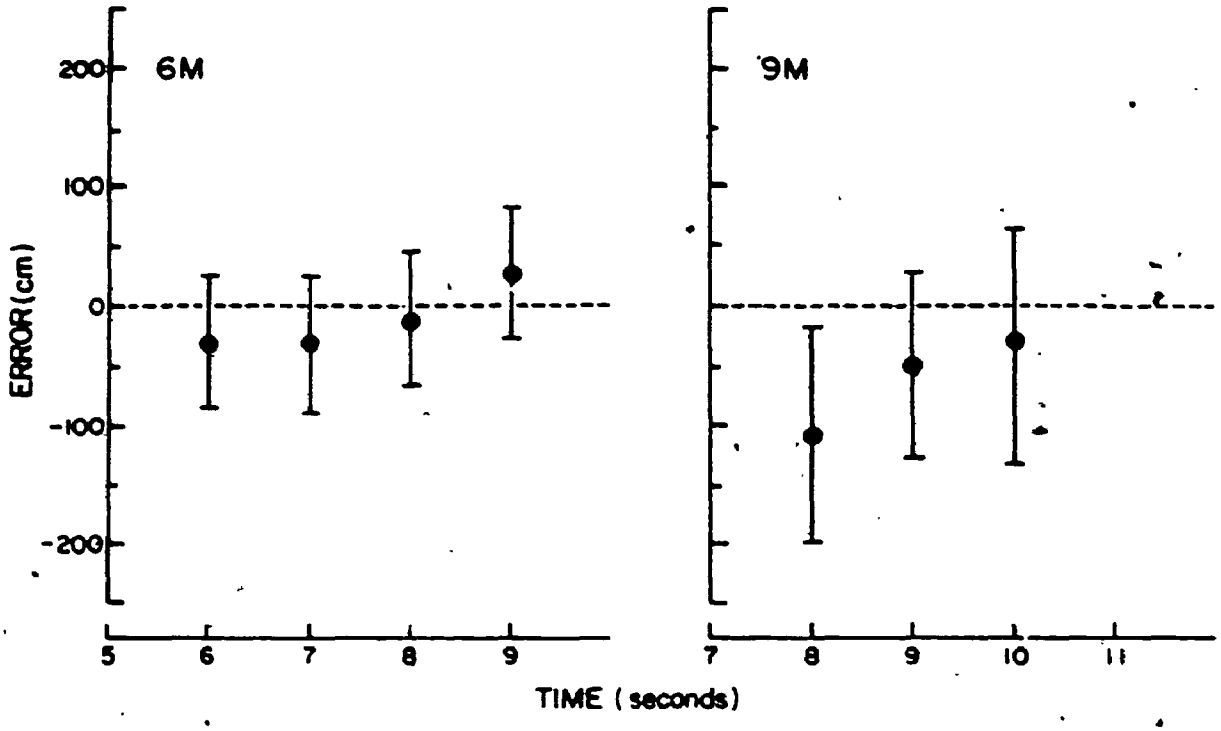
Performance variability

The standard deviation of the mean signed error which combines intrasubject and intersubject sources of variance in much the same way Thomson (1980, 1983) did, the standard deviation of the mean constant error and mean variable error were compared (see Figure 2). Performance variability increased when intersubject and intrasubject sources of variance were combined. The standard deviation of signed errors was greater than both variable errors and standard deviations of constant errors at all distances. Combining sources of variance did not result in a sharp decrease in accuracy at 9 m, the distance where mean walk-time exceeded 8 s. Performance variability increased with distance in an apparently linear fashion regardless of how it was calculated. Trend analyses were done only on variable error.

Separation of time and distance effects

Figure 3 shows the effects of walk-time, independent of target distance. Mean signed errors at the 6 and 9 m target distances were plotted separately with respect to the time taken to complete each walk. At each target distance, the standard deviation associated with the mean signed error was the same whether a walk took more than or less than Thomson's critical time of 8 s. The previously mentioned increase in standard deviation with increased target distance was still present. In other words, standard deviations were larger at 9 m than at 6 m. For each distance, as walk-time increased, mean signed errors simply ranged from those that undershot the target to those that

Figure 3. Mean signed errors and standard deviations (cm) for the 6 m and 9 m target distances are plotted with respect to time taken to complete a walk. Walk-times were rounded off to the nearest second and errors were sorted into time-bins accordingly. Intersubject and intrasubject sources or variance were combined because of the variable number of trials in each time-bin from each subject. No statistical procedures were performed on these data.


6M
9M
200
100
0
-100
-200
ERROR (cm)
5
6
7
8
9
7
8
9
10
11
TIME (seconds)

approached or overshot the target.

EXPERIMENT 2

In Experiment 1, being able to see a target produced highly accurate locomotor performance, removal of that visual feedback resulted in a decrement in performance. Performance deteriorated in a systematic way when subjects walked with their eyes closed -- as target distance increased, accuracy decreased. There was no evidence for a short-term memory of target locations. Even when time and distance effects were examined separately, walks that took more than 8 s were no more variable than walks that took less than 8 s. In order to examine Thomson's proposed short-term memory more systematically, a second experiment was undertaken. In this experiment, delays were introduced between viewing the target and walking. This manipulation made the time taken to reach the same target less than 8 s on some occasions and more than 8 s on others.

Method

Twenty right-handed paid volunteers (10 male and 10 female) with normal or corrected vision and ranging in age from 19 to 30 (mean = 22.85, s.d = 3.22 years) walked to a target placed at 3, 6, 9, 12, or 15 m in a corridor. The apparatus and methods used in this experiment were the same as in Experiment 1, with the following exceptions. In this experiment, delays were introduced between viewing the target and walking. After viewing the target for 5 s, subjects were signalled to close their eyes following which they either walked immediately or waited with eyes closed for 2 or 4 s before they walked. Five trials

at 5 distances (3, 6, 9, 12, and 15 m) and 3 delays (0, 2, and 4 s) were presented randomly for a total of 75 trials. A short break was given halfway through the experiment. This procedure deviated from that used by Thomson (1980, 1983) who presented the delay conditions separately, in order of increasing delay. It was assumed that the randomization of distances and delays used in the present experiment would eliminate any effect that order could produce, such as a deterioration in performance due to fatigue.

At the end of the experiment, subjects were questioned about any strategies they might have used to aid their performance. Following initial nondirective questioning, subjects were asked if they had estimated the number of paces or steps the target was away from them.

There was no overlap of subjects between this experiment and the previous one. All subjects were unaware of the purpose of the experiment and specific feedback about performance was not given until the last task had been completed.

Data analysis

Constant and variable error scores and walk-times were calculated as outlined in Experiment 1. Constant and variable errors were each subjected to a 3 (delay) X 5 (distance) repeated measures analysis of variance. Variable errors were also subjected to a trend analysis.

Results

Effect of target distance

Constant error. In this experiment, there was no overall tendency to undershoot far targets (effect of distance: $F(4,72) = 1.51$,

$p > .05$). As is shown in Figure 4, most walks varied around the target. However, one subject overestimated the distance to all targets. The constant error of this subject was more than 3 standard deviations above the mean (see chapter 4, Figure 25). Mean constant errors calculated without the data from this subject showed the same pattern of undershooting found in Experiment 1 (effect of distance: $F(4,68) = 2.47$, $p = .053$).

The standard deviations of constant errors increased with target distance, just as they did in Experiment 1. Nevertheless, at each distance, the standard deviations were similar whether the subjects walked immediately or waited before they walked.

Variable error. As Figure 5 shows, variable error increased with distance (effect of distance: $F(4,76) = 60.13$; $p < .0001$). For each of the delay conditions, variable error increased linearly as a function of distance (0 s delay: $F(1,19) = 56.59$, $p < .0001$; 2 s delay: $F(1,19) = 57.75$, $p < .0001$; and 4 s delay: $F(1,19) = 76.33$, $p < .0001$). There were no significant cubic or quadratic trends for any condition.

Effect of time

There was no sudden decrease in performance accuracy associated with walks that took more than 8 s. Neither variable error (see Figure 5) nor the standard deviation of constant error (see Figure 4) increased abruptly at the distance where more than 8 s had elapsed between viewing the target and the completion of a walk. Moreover, delay had no overall effect on performance accuracy (constant error: ($F(2,36) = 1.65$, $p > .05$; variable error: $F(2,38) = 0.46$, $p > .05$). Walk-times for each delay and distance are shown in Table 2. Since

Figure 4. Mean constant errors and standard deviations (cm) for subjects walking with eyes closed to distances between 3 and 15 m without delay (closed circles), after a 2 s delay (open circles), and after a 4 s delay (closed triangles) for Experiment 2 (n = 20). The arrows indicate the distances at which the average time taken to reach the target was more than 8 s.

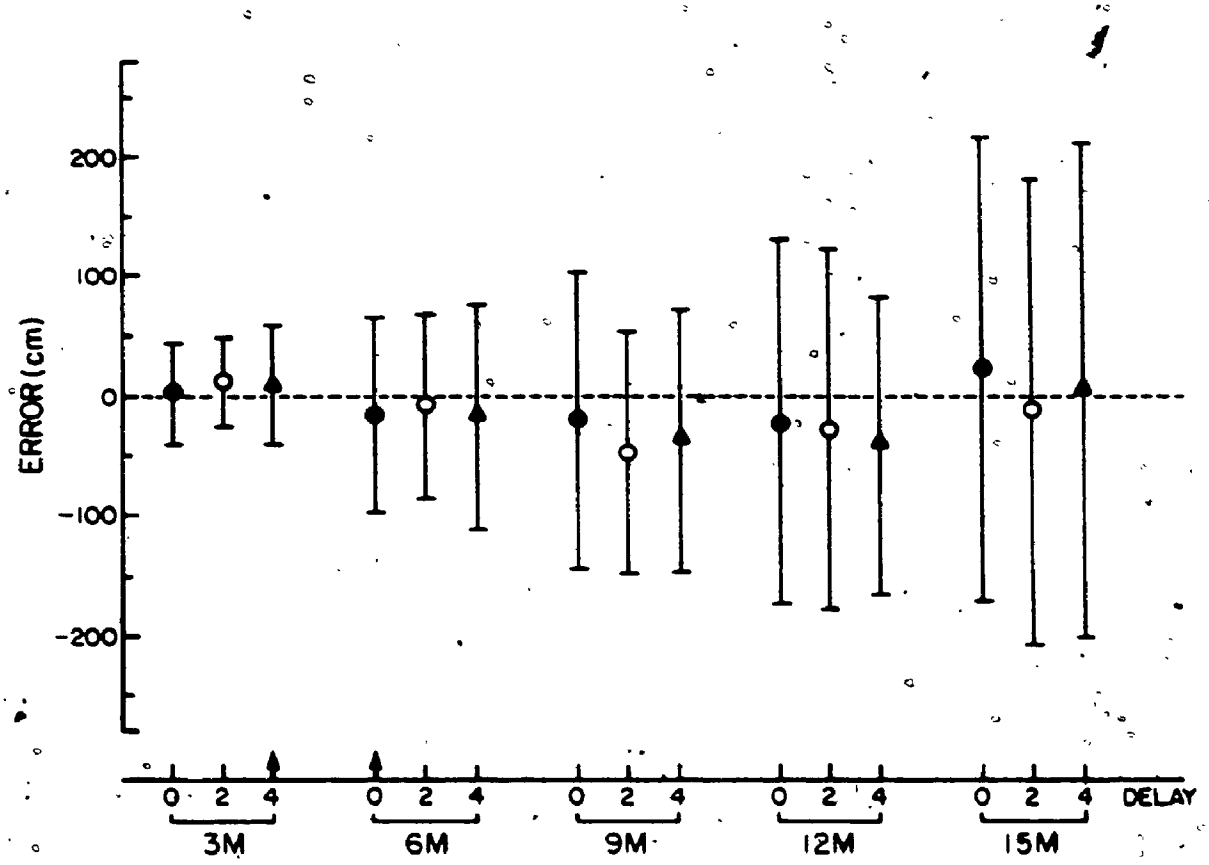

200
100
0
-100
-200
ERROR (cm)
0 2 4
0 2 4
0 2 4
0 2 4
0 2 4
DELAY
3M
6M
9M
12M
15M

Figure 5. Mean variable errors for Experiment 1 (n = 20; open circles), Experiment 2 (n = 20; closed circles), Experiment 3 (n = 14; closed triangles), and for a selected sample from Experiment 3 (n = 8; open triangles).

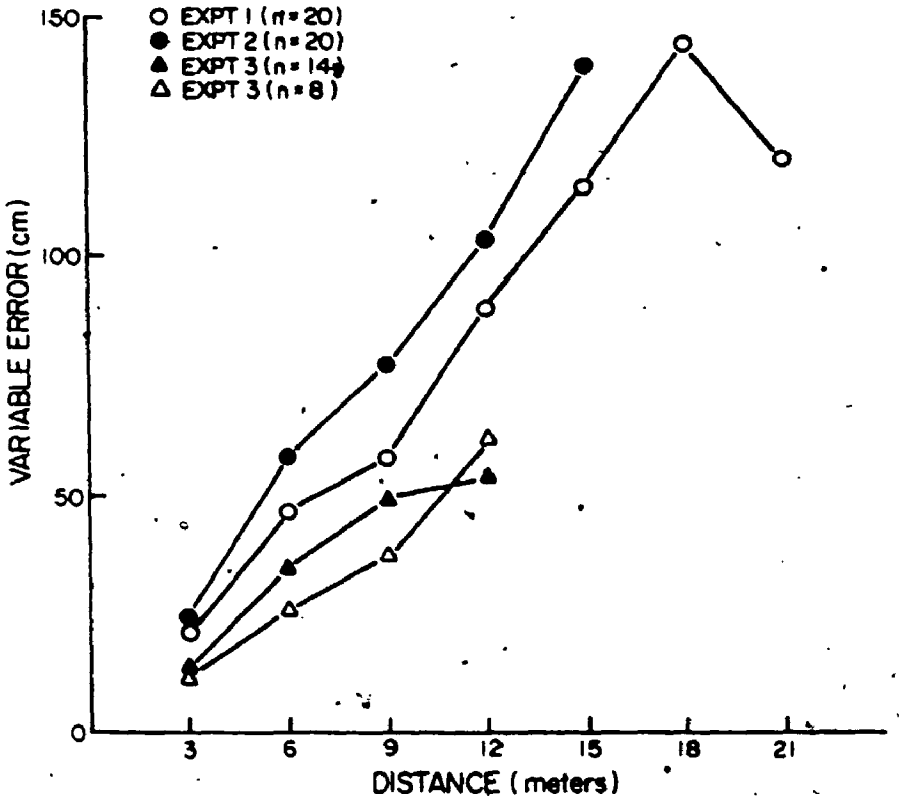

EXPT 1 (n=20)
EXPT 2 (n=20)
EXPT 3 (n=14)
EXPT 3 (n=8)
VARIABLE ERROR (cm)
150
100
50
0
3
6
9
12
15
18
21
DISTANCE (meters)

Table 2

Mean times (including delay) and standard deviations (s.d.) in seconds (s) taken to complete all walks (n = 20)

	Distance (m)				
	3	6	9	12	15
Time (s)					
Delay = 0 s					
(mean)	5.32	8.01	10.59	13.41	16.87
(s.d.)	1.28	1.82	1.92	2.60	3.71
Delay = 2 s					
(mean)	7.07	9.67	12.02	15.23	18.43
(s.d.)	1.22	1.68	1.78	2.43	3.91
Delay = 4 s					
(mean)	9.34	12.02	14.52	17.30	20.62
(s.d.)	1.04	1.95	1.70	2.76	3.47

most walks took more than 8 s, the range over which performance accuracy could decrease with delay was limited. Additionally, when the effects of time and distance were separated, accuracy did not decrease for walks that took more than 8 s. Time taken to complete a walk related in a consistent way to distance walked. The relation was the same as that illustrated by Figure 2 (Experiment 1). Once again, at any one distance the shortest mean walk-times were obtained on undershoots of a target, while the longest mean times were obtained on overshoots.

Strategy

All but one subject reported using some sort of strategy to aid performance. Eighteen of the 20 subjects said that they consistently estimated the number of paces the target was away from them. A majority of the subjects reported using a pacing strategy without directed questioning. When asked how they helped themselves perform the locomotion task, they gave responses such as, "I counted the number of steps I thought the target was away". This estimate could easily be rehearsed during the 2 or 4 s delay, thereby allowing the subjects to perform as if they had walked immediately.

Discussion

Experiments 1 & 2

The results of Experiments 1 & 2 suggest that distance, but not time can affect performance accuracy in target-directed locomotion. No evidence was found to suggest that a short-term visuospatial memory was in operation. First, the relation between distance and accuracy was

linear. There was no distance or time at which locomotor accuracy decreased abruptly. If there had been an abrupt deterioration in accuracy of the type Thomson (1980, 1983) found, both linear and cubic components of the trend analyses would have been significant. Second, increasing the time taken to reach the same target to more than 8 s did not result in a decrease in accuracy. It is possible, however, that the pacing strategy used by most subjects in Experiment 2 could account for the lack of effect of delay, although such verbalization strategies have not been reported by Thomson to be a factor affecting performance on this task. Nevertheless, the absence of any instructions about the use of verbal strategies may well have led to the results reported here.

A careful examination of the findings reported by Thomson (1980, 1983) revealed that performance was more accurate and less variable, when subjects took 8 s or less to reach targets at 3, 6, and 9 m than it was in the present experiments. For these distances, subjects in Thomson's experiments performed as if they had full vision. The results of Experiment 1, reported here, showed that subjects walking with their eyes closed did not perform as well as they did with their eyes open at any distance beyond 3 m. In addition, Thomson found that 84% of walks to the 3, 6, and 9 m targets were within 24 cm of the target when there was no delay. In the present experiments, the most accurate performances with eyes closed were at 3 m, where only 55% (Experiment 2) to 60% (Experiment 1) of walks without delay were within 24 cm of the target. Moreover, the standard deviation of signed error reported by Thomson showed very little change with distance when walks

took less than 8 s. The linear increase in variable error, reported here, appeared to be suppressed at 6 and 9 m in Thomson's experiments. However, at 12 m (also at 9 m after a 2 s delay, and 6 m after a 4 s delay) the standard deviations reported by Thomson were within the range found here when both the intrasubject and intersubject sources of variance were combined. The question, therefore, is not why performance was so inaccurate at 12 m when there was no delay and so inaccurate at 6 and 9 m after a delay, but why Thomson found performance to be so consistent and accurate at 3, 6, and 9 m when there was no delay.

It should also be noted that mean walk-times were shorter in Thomson's (1980, 1983) experiments than they were in the experiments reported here. Evaluation of the effect of the duration of a walk was complicated by the fact that Thomson stopped timing the subject when they reached the target. Therefore, the times he presented are not an accurate indication of the amount of time the subject walked. All mean walk-times and their standard deviations are underestimated and thus, a performance time of 8 s reported by Thomson does not necessarily mean that the subjects walked for only 8 s. In many cases, they will have walked for quite a bit longer. The total time taken to complete a walk (the measure used in the present experiments) appears to be a more appropriate indication of what the subject believed the 'correct' distance to be and thus, the remembered target location. Indeed, it could be argued that in this context, the actual target location was somewhat irrelevant.

In the present experiments, the problem of confounding distance and time effects was addressed by plotting them separately. Even when distance and walk-time effects were separated, no evidence of a decrease in accuracy with times over 8 s was found. If the times reported by Thomson had included the time to complete all walks, including those that overshot the target, then at a particular distance, walks that took less than 8 s could have been compared to those that took more than 8 s. Without this evidence, Thomson has not demonstrated conclusively that the proposed short-term memory decays abruptly after 8 s.

EXPERIMENT 3

In spite of reservations about the phenomenon reported by Thomson (1980, 1983), another attempt to replicate his findings was undertaken. I felt that it was necessary to show very definitively whether Thomson's results could be reproduced when the methodology he used was duplicated as closely as was possible. Several changes were introduced to the method in the following experiment in an attempt to reduce the variance at near targets, and to eliminate the possible effects of a pace-estimation strategy. In order to increase accuracy, subjects were trained to walk with eyes closed to targets positioned at distances similar to those used on the experimental trials. Thomson (1985, 1986) suggested that training with visual feedback, not just practice walking with eyes closed, was necessary for accurate performance on this task. The details of the training provided in Thomson's (1983) paper do not stress the same aspects that he later came to view as important

(Thomson, 1986). Thomson (1983) simply states,

> All subjects were given a short practice session to accustom themselves to blind walking. This session was conducted some distance away from the experimental layout and involved walking to designed random points. This practice session was principally concerned with getting subjects to walk in a natural and uninhibited manner (a vital condition in this experiment) and was terminated as soon as this was achieved. This session lasted approximately 5-10 min. (p. 429)

In a recent paper, Thomson (1986) reviews his methodology, but does not present any new data. With reference to the training his subjects received in the experiments published in 1980 and 1983, he now states,

> I have always stressed that practice is a vital preliminary to this kind of experiment where subjects are asked to do something essentially unnatural. Walking with eyes shut goes against the grain, and subjects invariably feel uncomfortable at doing so, especially at longer distances or for extended periods. In my view, the only way to overcome this is to give them practice at the task, away from the testing area, using a wide range of distances and giving them <u>feedback</u> as to their accuracy. This is vital to instilling a sense of confidence in subjects who otherwise are unwilling to walk in an unhesitating manner. (p. 393, emphasis Thomson's)

While no information was given about the range of distances used or the accuracy subjects were required to achieve during the practice session,

an effort was made in Experiment 3 to carry out the kind of training that Thomson believes is necessary. As will become apparent, despite this, no evidence of a highly accurate short-term memory was found.

The range of distances over which delay could be effective in producing a deterioration in performance was increased by instructing the subjects to walk briskly. Subjects were also instructed not to use a pace-estimation strategy on the task. Thomson's methodology was more closely duplicated by presenting the conditions in order of increasing delay and by presenting one trial at each distance in random order before another block of trials was presented (random blocks as compared to a completely randomized presentation; Thomson, 1985).

Method

Fourteen right-handed paid volunteers (7 male and 7 female) with normal or corrected vision and ranging in age from 19 to 33 (mean = 23.87, s.d = 4.49 years) walked to a target (as described in Experiment 1) in a large field (approximately 20 m by 20 m). The field was bordered on three sides by a sidewalk. The edge of the sidewalk at one end served as a start-line. Veering errors were minimized by the training subjects received before they started the experiment. Error data were obtained from a tape measure laid out on the ground in a straight line to the right of where the subject was required to walk. The white noise used to mask environmental noise in the previous two experiments was discontinued in this and all following experiments (Thomson, 1985).

All subjects were naive as to the purpose of the experiment and

there was no overlap of subjects between this experiment and previous experiments.

Training

The target was placed at randomly chosen near (approximately 1-5 m), middle (approximately 5-10 m), and far (approximately 10-15 m) distances. Subjects were instructed to form a mental image of the target and imagine themselves walking towards the target, but not to estimate the number of steps or paces the target was away from them. When the subjects had the target "firmly fixed in their mind", they were to close their eyes and walk briskly along a path to the left of the target. When the subjects stopped walking, they were asked to open their eyes to see how far they were from the target. Practice was given until the subject walked to within 30-40 cm of the target at two different near, middle, and far distances. The minimum number of practice trials was 6. The practice session took place in a different part of the field from the experimental trials.

Experimental trials

Three blocks consisting of 1 trial at each of the 3, 6, 9, and 12 m target distances were presented under 3 conditions. In the first condition, subjects walked immediately after closing their eyes. For the next condition, they closed their eyes and waited for 2 s before they walked and for the last condition, they waited for 4 s before walking. Feedback was not given on experimental trials. After every 2 blocks, subjects were given practice with feedback walking to targets. A minimum of 1 practice trial at near, middle, and far (as defined above) distances was given. Practice was continued at a distance until

the subject walked to within 30-40 cm of the target.

Data Analysis

Constant and variable errors were calculated as outlined in Experiment 1. Constant and variable errors were each analyzed with a 3 (delay) X 4 (distance) repeated measures analysis of variance. Variable errors were also subjected to a trend analysis.

Results

Effect of target distance

Constant error. In this experiment, as in Experiment 1, a significant effect of distance on constant error ($F(3,36) = 12.42$, $p < .0001$) was the result of an undershoot of far targets. As is shown in Figure 6, walks at 3 m varied around the target after which distance was progressively underestimated.

Variable error. Variable error increased with distance (see Figure 5; $F(3,39) = 36.60$, $p < .0001$). Once again, there was no distance at which variable error increased abruptly. For all delays, there was a highly significant linear relation between variable error and distance (0 s delay: $F(1,13) = 36.51$, $p < .0001$; 2 s delay: $F(1,13) = 48.07$, $p < .0001$; 4 s delay: $F(1,13) = 15.18$, $p < .005$). No significant effects were found for either cubic or quadratic functions.

Effect of time

The times taken for all walks are shown in Table 3. It should be noted that subjects in Experiment 3 walked faster than subjects in the previous two experiments (Tables 1 and 2). Increased walking speed

Figure 6. Mean constant errors and standard deviations (cm) for subjects walking with eyes closed to distances between 3 and 12 m without delay (closed circles), after a 2 s delay (open circles), and after a 4 s delay (closed triangles). The arrows indicate the distances at which the average time taken to reach the target was more than 8 s.

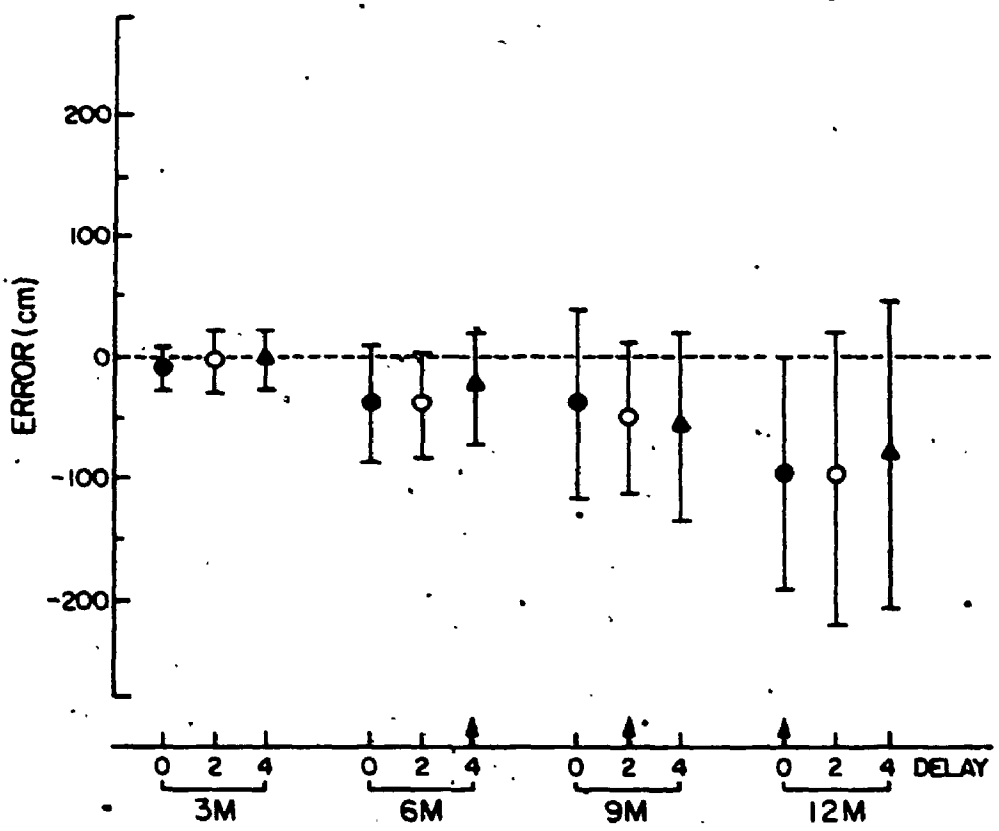

200
100
0
-100
-200
ERROR (cm)
0 2 4
0 2 4
0 2 4
0 2 4
DELAY
3M
6M
9M
12M

Table 3

Mean times (including delay) and standard deviations (s.d.) in seconds (s) taken to complete all walks (n = 14)

	Distance (m)			
	3	6	9	12
Time (s)				
Delay = 0 s				
(mean)	4.05	6.02	7.87	9.25
(s.d.)	0.30	0.51	0.69	0.76
Delay = 2 s				
(mean)	5.75	7.43	9.37	11.04
(s.d.)	0.62	0.59	0.84	1.14
Delay = 4 s				
(mean)	7.43	9.84	11.39	13.02
(s.d.)	1.24	0.82	0.93	1.18

allowed for the possibility that delays could affect accuracy over a range of distances. For instance, when the subjects walked immediately after viewing the target, all walks to 3, 6, and 9 m took less than 8 s, but when subjects waited for 2 s before walking, walks to 3 and 6 m took less than 8 s. Nevertheless, no abrupt increase in standard deviation of constant error (see Figure 6) or in variable error (see Figure 5) was apparent at 12 m (0 s delay), 9 m (2 s delay) or at 6 m (4 s delay). Again, delay did not produce an overall effect on constant error ($F(2,24) = 0.35$, $p > .05$) or variable error ($F(2,26) = 1.51$, $p > .05$).

Performance accuracy

Practice did not lower variable error (Figure 5) or the standard deviation of the constant error at near targets selectively (see Figure 6). Highly accurate performance at 3, 6, and 9 m (delay = 0 s) would have been necessary to obtain the effect Thomson (1980, 1983) found. Although variable errors were lower than those found in Experiments 1 and 2 (see Figure 5), all distances were equally affected. Of course, it is also possible, but less likely that the overall improvement in accuracy seen in this experiment was due to any or all of the following: the smaller number of trials, the removal of the white noise, the use of an imaging strategy, and/or the blocking of delays and distances.

Subjects in the present study were not as accurate as Thomson (1980, 1983) reported. Thomson found that for 84% of the walks that took less than 8 s, subjects stopped walking within 24 cm of the target. In the present experiment, comparable accuracy was found only

for the 3 m target. At 3 m, on 74% of the walks without a delay subjects stopped walking within 24 cm of the target, while at 6 and 9 m, 41% and 26%, respectively, of performances attained an accuracy of 24 cm or less.

It is possible that subjects who were unable to walk to a nearby target accurately showed a different pattern of results than subjects who were accurate. Thus, the effect of locomotor accuracy on performance variability was evaluated further by looking at the error pattern of the "best" subjects (subjects whose mean absolute error was 60 cm or less at the 9 m target for walks without a delay). Variable errors in the reduced sample (n = 8) were lower than those of the total sample, but they were still not flat between 3 and 9 m (see Figure 5). More importantly, variable error at 12 m was only slightly increased. That is to say, the relation between performance variability and distance remained linear. Trend analysis showed a significant linear component ($F(1,7) = 17.34$, $p < .005$) for walks without a delay, but neither cubic nor quadratic components. For the reduced sample, 79% of walks without delay at 3 m, 50% at 6 m, and 33% at 9 m were within 24 cm of the target.

Discussion

Again, it is clear that distance, not elapsed time, was the factor controlling performance accuracy. No support was found in this study for the highly accurate short-term memory of target distances proposed by Thomson (1980, 1983). Even with practice, performance at the 6 and 9 m targets was not as accurate or as invariant as that

reported by Thomson. A linear relationship between distance and variable error was preserved, even when subjects were chosen on the basis of accurate performance at the 9 m target.

The elimination of pacing strategies did not have any apparent effect on the pattern of performance accuracy. Subjects' performance did not deteriorate when they were not able to rehearse verbally. It was interesting that a pace-estimation strategy appeared to be the preferred method of solving this apparently visuospatial problem. Verbalization has been reported to aid performance on other tests of non-verbal memory (Glanzer & Clark, 1962). Moreover, Laabs (1981) warns investigators to control for cognitive strategies in experiments examining motor memory.

If a highly accurate short-term memory of target distances of the type that Thomson (1980, 1983) postulated does not exist, then what is the nature of short-term memory processes for target distances? If longer delays were introduced between viewing a target and walking would performance deteriorate?

EXPERIMENT 4

An additional experiment was performed in an attempt to determine if a short-term memory of target distance could be demonstrated, and to determine the circumstances under which time would be a factor controlling locomotor accuracy. A relatively long delay was chosen to optimize the possibility of obtaining a deterioration in performance.

Method

Twelve right-handed paid volunteers (5 female and 7 male) with normal or corrected vision and ranging in age from 19 to 25 (mean = 22.21, s.d. = 2.75 years) walked to a target in a corridor (as described in Experiment 1). Subjects were pretrained in the same way they had been in Experiment 3. Practice was continued until criterion performance was attained.

One trial at 3, 6, 9, and 12 m was randomly presented in 3 blocks in each of two conditions. The conditions were: eyes closed with no delay and eyes closed with a 30 s delay. Presentation of the conditions was balanced across subjects. No feedback was given on experimental trials. Additional practice was given between each condition.

There was no overlap of subjects between experiments. None of the subjects had any knowledge about the purpose of the present investigations.

Data Analysis

Constant and variable errors were calculated as outlined in Experiment 1. Constant and variable errors were each analyzed by a 2 (delay) X 4 (distance) repeated measures analysis of variance. Variable error was also subjected to a trend analysis.

Results

Effect of target distance

Constant error. As in Experiments 1 and 3, a significant effect of distance ($F(3,30) = 11.32$, $p < .0001$) on constant error was evident as an undershoot of far targets. The basic pattern of constant errors and their standard deviations was the same as in previous experiments: namely, as distance increased, the standard deviation of constant error increased. There appeared to be less of a tendency for the subjects to undershoot the far targets after the delay, although on the average the 9 and 12 m distances were still underestimated after a 30 s delay.

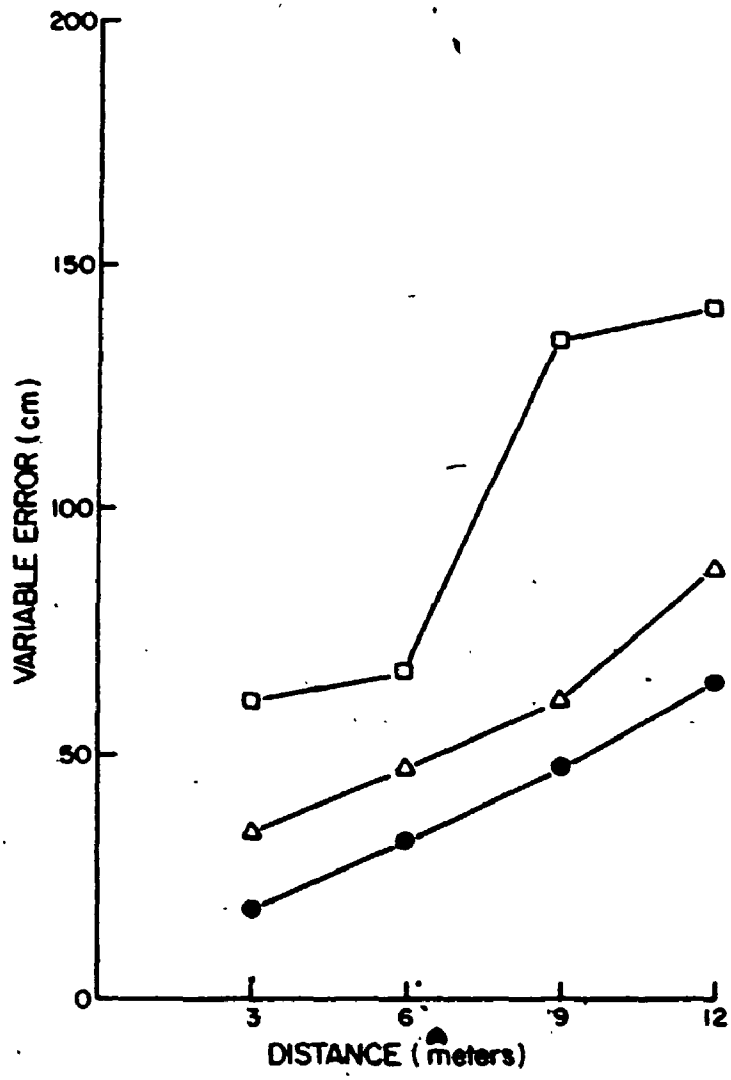
Variable error. For all walks, distance had a significant effect on variable error ($F(3,33) = 13.11$, $p < .0001$; see Figure 7). Figure 7 also shows that the relation between variable error and distance for both walks with and without delay was linear (0 s delay; $F(1,11) = 14.28$, $p < .005$; 30 s delay: $F(1,11) = 12.03$, $p < .010$). Neither cubic nor quadratic functions were significant.

Effect of time

Variable error was significantly larger after a 30 second delay than it was when there was no delay ($F(1,11) = 16.41$, $p < .005$). The difference between mean variable errors was significant only at 12 m (LSD: $df = 39$, $p < .05$). The 30 s delay did not affect constant errors (effect of condition: $F(1,10) = 1.27$, $p > .05$).

In the present experiment, as in the previous experiments, subjects reached the 9 m target in about 8 s (mean = 8.2, s.d. = 1.4). Waiting for 30 s before walking did not affect the walk-time of the subjects. For example, the time that elasped between viewing the 9 m

Figure 7. Average variable errors (cm) for subjects (n = 12) walking with eyes closed without delay (closed circles) and after a 30 s delay (open triangles). The standard deviations of signed errors (cm; n = 36: 3 repetitions for each subject at each distance) after the 30 s delay are also shown (open squares).


200
150
100
50
0
VARIABLE ERROR (cm)
3
6
9
12
DISTANCE (meters)

target and reaching it was 38.5 s (s.d = 1.7; the sum of a 30 s delay plus a 8.5 s walk-time). For the other target distances, the elapsed time was also approximatly equal to the 30 s delay plus the walk-time of the condition were subjects walked immediately.

Performance variability

When the standard deviation of signed error, the measure used by Thomson (1980, 1983), was calculated, a two-fold increase in standard deviation was found between 6 and 9 meters (see Figure 7). No such abrupt increase was evident in variable error. The results were plotted in this way to illustrate the problems that can be created by confounding sources of variance in the way that Thomson did.

Discussion

The results of this experiment give a clear demonstration that performance on a target-directed locomotion task deteriorates after a 30 s delay. Accuracy, as measured by variable error, decreased in an apparently linear fashion suggesting that forgetting occurred equally at each distance. On the basis of the present results, short-term memory of target distance may be expected to show a gradual rather than an abrupt deterioration with increasing time. Although accuracy was significantly affected by delay, the deterioration in performance was small. The fact that all distances were equally affected by the delay (no interaction between distance and delay) may suggest that wait-time and walk-time did not have a cumulative effect. Walks taking 35 s (3 m) were not affected any differently from walks taking 41 s (12 m). Decreased accuracy can be assumed to be due to a deterioration of the

initially perceived target position and not to errors that may have occurred while the subject was walking.

This experiment also gives a clear demonstration of the problems that can be created by confounding sources of variance. Variable error showed a linear increase with target distance while the standard deviation of signed error showed an abrupt increase at 9 m. The abrupt increase in the standard deviation of signed error resulted from different subjects walking to different locations relative to the 9 m target. The increase in variability that Thomson (1980, 1983) found may have been due to similar intersubject effects (Elliott, 1986 makes a similar point). This finding does not account for the highly accurate performance that Thomson found on walks that took less than 8 s, however.

CONCLUDING REMARKS

A number of important differences were found between the work of Thomson (1980, 1983) and the investigations reported here. First, target distance and not elapsed time was found to be the critical factor controlling accuracy of walks with eyes closed to targets up to 21 m away. There was no evidence for an effect of 2 or 4 s delays on locomotor accuracy; therefore, no evidence of a highly transient short-term memory. A less accurate, but more slowly decaying short-term memory for target distance was demonstrated. Second, the accuracy reported by Thomson for targets up to 9 m away could not be duplicated here. In the present experiments, subjects walking with their eyes closed did not perform as if they had full vision for

targets beyond 3 m. Increasing walking speed and pretraining did not result in either an increase in accuracy to the level of Thomson's subjects or in a demonstration of the short-term memory effect. Thomson's claim of a deterioration in performance rested on initially superior performance at certain targets. In the present experiments, training affected all target distances equally.

Other unresolved problems surround Thomson's data. Some of the issues are methodological, others are theoretical. A discussion of the theoretical issues will be presented later. Thomson (1986) states that the purpose of training the subjects was to make them comfortable with an unnatural situation -- walking with eyes closed. It appears, however, that the effect of his training was to allow for the appearance of superior performance at some targets, not simply more proficient performance on an uncommon task. In other words, the training was necessary in order to produce the short-term memory effect. Exactly what the training involved was not explained by Thomson (1983, 1986). Some manipulations during training would make the short-term memory data situation specific and uninteresting. Examples of such manipulations include, differential training at some distances and/or during some conditions. This type of training would be especially problematic if it involved some of the target distances used in the experimental conditions. Thomson, having been challenged, should present new data in which he delineates the precise nature of the training his subjects receive and in which the appropriate repeated measures analyses are used (see criticisms voiced here and those of Elliott, 1986). A justification for stopping the timing of a trial

when the subjects reached the target rather than when they stopped walking would also be informative.

An additional problem lies in the finding that the distance to far targets was significantly underestimated by subjects in 3 of the 4 experiments reported here. No tendency to undershoot far targets was evident in Thomson's data. It is not possible to determine whether the undershoots found in the present experiments were due to errors in perception of the target distance or errors in execution of the non-visually guided movements (motor errors). Both perceptual and motor tasks have been reported to show an underestimation of target distance for the more distant targets. The pattern of constant errors found here was reminiscent of this so-called 'range effect' (Searle & Taylor, 1948; Slack, 1953; Poulton, 1975). A range effect was particularly apparent in Experiment 4, where the average constant errors at 3 m overestimated the target distance, after which target distances were progressively underestimated.

Moreover, the data presented here show that a very basic psychophysical relation exists between error and target distance. All the experiments showed a linear relationship between variable error and target distance. Gibson and Bergman (1954) found that perceptual errors in estimating the distance to a target in an open field were a constant proportion of the target distance. This work and that of Harway (1963) suggests there is a linear increase in perceptual errors with distance. Others have reported similar distance effects in kinesthetically guided movements (Posner, 1967; Wooodworth, 1899). It is not possible from the studies undertaken here, to determine the

source of locomotor errors. However, on the basis of perception alone, an increase in errors with increased target distance would be predicted. The fact that Thomson (1980, 1983) found subjects were as accurate at 9 m as they were at 3 m suggests that errors in perception had been eliminated in his investigations. Furthermore, on walks taking less than 8 s, motor errors must also have been eliminated. As was stated above, in the present experiments, pretraining with visual feedback of the type Thomson (1985, 1986) recommends did not reduce locomotor errors selectively (for walks taking less than 8 s) or sufficiently (to the level of visually guided walks) to produce evidence of a highly accurate short-term memory of target distance.

Clearly, memory of spatial locations exists, but a short-term visuospatial memory of the type that Thomson (1980, 1983) described now seems unlikely (also see Elliott, 1986). Rather than proposing a memory that ensures superior performance over a narrow range of distances and/or times, a more reasonable suggestion, one supported by the evidence presented here, is that memory for target locations is not accurate and decays slowly over time. In a recent experiment in our laboratory, a very similar type of slowly decaying short-term memory was found on a reaching task. Subjects pointed to targets that were located up to 30 cm away on the surface of a table. When subjects pointed with their eyes closed, delays of 8 s had no effect on reaching accuracy. Delays of 30 s, however, produced a significant increase in variable errors. Like variable errors on the locomotion task, variable errors on the pointing task increased in a linear fashion with increased target distance. In the pointing task, the 30 s delay

increased variable errors at each target distance in very much the same way that the 30 s delay increased variable errors in the locomotion task (Experiment 4).

Other evidence of a gradual rather than an abrupt forgetting of target locations comes from the finding that a subject's ability to fixate a previously illuminated target (75 cm away in a darkened room) deteriorates in a systematic way with increased delay (Skavenski & Steinmah, 1970). This finding is consistent with the gradual, not abrupt, forgetting found on other target location tasks (Dale, 1973). A systematic deterioration in performance, interpreted as a decay in short-term memory, has also been noted on non-visually guided motor tasks (see Adams & Dijkstra, 1966, for example).

In summary, locomotor accuracy in the absence of visual feedback was found to depend on target distance and a short-term memory which deteriorated when subjects waited 30 s between viewing the target and walking.

CHAPTER 2

TARGET-DIRECTED LOCOMOTION: FURTHER EVALUATION

In the previous chapter, visual feedback, target distance, and delays of 30 s were all found to affect locomotor accuracy in a target-directed locomotion task. In this chapter, a more detailed examination of the effects of visual context was undertaken.

Recently, investigators interested in motor behavior have begun to recognize that vision is important in the control of many behaviors (see for example, Gibson, 1958, 1979; Lishman & Lee, 1973). Over the past few years, the role of vision in the control of reaching and grasping has been examined (see Fisk & Goodale, 1985, for example). Few experimental investigations, however, have considered how vision is used to control locomotor accuracy (Elliott, 1986; Strelow & Brabyn, 1981; Thomson, 1980, 1983).

The following two experiments were designed to examine the role of visual context in the control of accurate locomotion directed to a target in the immediate environment. Some of the questions addressed in these investigations were: (1) would vision of the area around a target aid performance in the absence of the target itself; (2) could vision be used to estimate the distance to be walked in the absence of relevant contextual information; and (3) how does blind locomotion compare to walks with limited visual feedback?

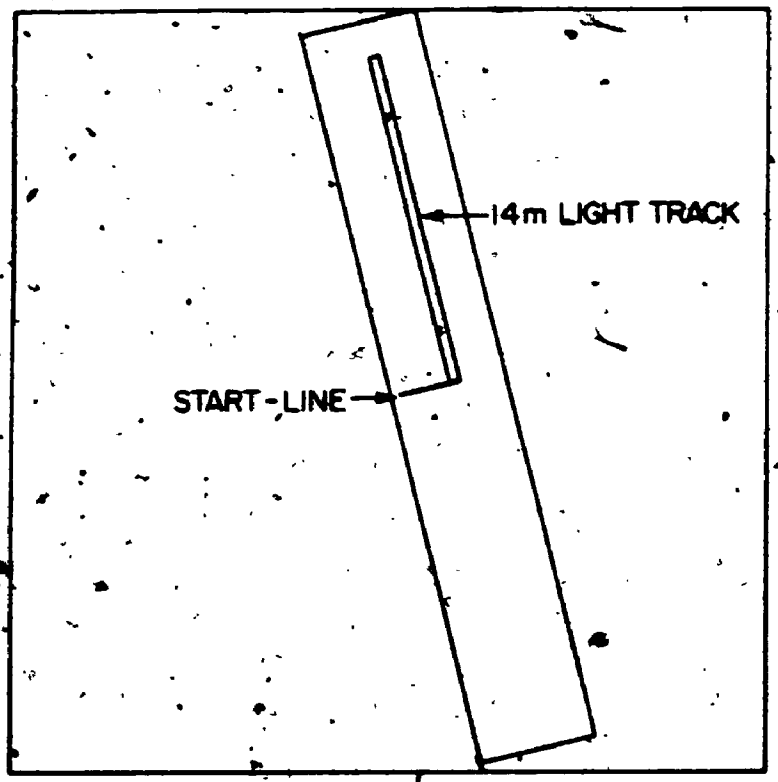
EXPERIMENT 5

Method

Five male and 5 female right-handed paid volunteers with normal or corrected vision and ranging in age from 20 to 35 years (mean = 25.5, s.d. = 5.54) served as subjects. The subjects were naive as to the purpose of the experiment which lasted about 2 hours and took place in a well-lit gymnasium. The apparatus consisted of a 14 m light-track with independently operating lights positioned at 1, 3, 5, 7, 9, and 11 m. The track was covered by translucent plastic and a continuous length of white material which made the lights visible only when illuminated. The light-track was placed on 30 m of 2.5 m wide plain brown paper and was positioned diagonally and off-center in one half of the gym (see Figure 8).

Prior to beginning the experiment, subjects were given practice walking with their eyes closed. Subjects were not encouraged to practice walking to any particular target or for any particular distance. On experimental trials, subjects were instructed to close their eyes as soon as they saw the target-light which remained illuminated for 200 ms. Subjects were then told to walk along a path to the left of the light-track immediately or to wait with their eyes closed for 2 or 4 s before they walked. They were instructed to stop walking when they believed the front of their toes lined up with the position of the target-light just presented to them. Three repetitions at each distance and delay (54 trials total) were presented randomly in each of the following conditions:

Figure 8. The 14 m light-track was positioned in the middle of a continuous sheet of plain brown paper which marked the area of locomotion for walks both in the direction of the target and in the opposite direction. The dimensions of the gym were approximately 30 X 30 m.



LIGHT TRACK SET-UP

Condition 1. Subjects walked with eyes closed and were led back to the start point by the experimenter. In this condition, subjects had to rely on a memory of the target distance and an internal method of determining when they had walked the correct distance to perform accurately.

Condition 2. Subjects turned 180°, positioned themselves behind the start-line, and walked with eyes open in the direction opposite to the target. Accurate performance relied on a memory of the target distance. Visual information was available to determine the distance walked, but not the precise location of the target.

Condition 3. Subjects walked with eyes open in the direction of a target flashed for 200 ms. Vision provided information about the distance walked and possibly also about cues near the specific target locations. Although the presence of the brown paper reduced the proximity of markings on the gym floor to the target-lights, subjects could have used these markings to help remember the target location after the light had gone out.

Condition 4. Subjects walked to targets that remained illuminated for the duration of the walk twice for each target distance (12 trials total). Full visual feedback was available on these walks.

Data Analysis

For each trial, the distance walked was recorded. For walks in the direction of the target, measurements were taken directly from a tape measure positioned behind the track. On walks in the opposite direction to the target, the location where the subject stopped walking was marked by a coded sticker placed on the underside of the brown

paper. For these trials, measurements were taken at the end of the experiment. In all cases, only straight line errors were calculated since deviations from a vertical path were limited by asking subjects to walk on the paper. Feedback about performance accuracy was given at the end of the experiment.

For each subject, signed, constant, absolute, and variable errors were calculated. Absolute error which was calculated by taking the absolute value of signed errors averaged over the different trials at a given distance was analyzed in this and the following experiments. Absolute error was included in the analyses because I considered it important to examine the effect of target distance and visual context all types of error. It should be noted, however, that the use of absolute error has been criticized by Roy and Schultz (1973).

The delays of 2 and 4 s did not affect locomotor accuracy. The data, therefore, were collapsed over delay. Since delay had no effect on performance, collapsing over delay simply served to increase the number of observations at each distance. Constant, variable, and absolute errors were each subjected to a 4 (condition) X 5 (distance) repeated measures analysis of variance. Post hoc LSD tests were used to evaluate significant effects. The relation between variable error and distance was analyzed for linear, quadratic, and cubic components using a trend analysis. Absolute errors were also subjected to a trend analysis.

Results

Constant error. There was a tendency for condition to affect constant errors ($F(3,27) = 2.77$, $p = .061$; see Figure 9). When subjects walked in the direction of the target, there was a tendency to undershoot the targets. Undershoots occurred whether the subjects had their eyes open or closed when they walked to a brief target. For walks to a persistent target, subjects did not undershoot or overshoot the target. When subjects turned and walked in the opposite direction, targets at all distances were overshot. Target distance did not have a significant effect on performance ($F(5,45) = 0.87$, $p > .05$) in any condition.

Absolute error. Aside from the highly accurate performance to constantly illuminated targets, performance was most accurate when subjects walked with eyes open to a target flashed for 200 ms. It was less accurate when they walked toward the target with eyes closed. Performance was least accurate when subjects turned and walked with eyes open in the direction opposite to the target (effect of condition: $F(3,27) = 9.58$, $p < .005$).

As Figure 10 shows, in all conditions, except for walks to a persistently illuminated target, performance deteriorated as the distance to the target increased ($F(5,45) = 6.41$, $p < .005$). Errors increased more slowly for visually guided walks toward a target flashed for 200 ms than they did in the other two conditions (condition by distance interaction: $F(15,135) = 1.78$, $p < .05$). Neither walks with eyes open to a persistent target ($F(1,9) = 3.99$, $p \geq .05$) nor walks with eyes open in the direction opposite to the target ($F(1,9) = 2.84$, $p >$

Figure 9. Mean constant errors (cm; n = 10) collapsed over all target distances are shown for walks with eyes open to a persistent target, and for walks with eyes open and closed toward a brief target. Walks with eyes open in the opposite direction to target are also shown.

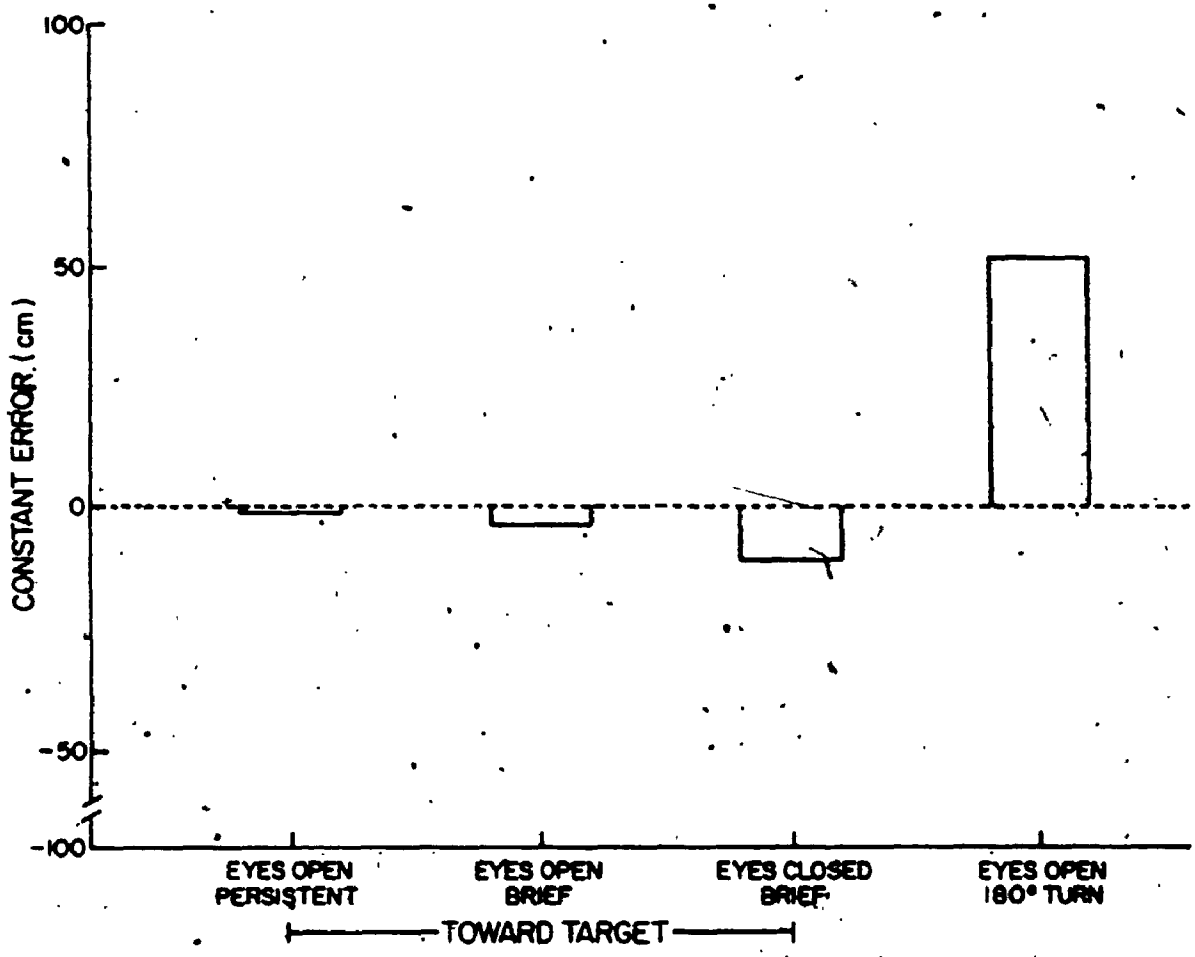
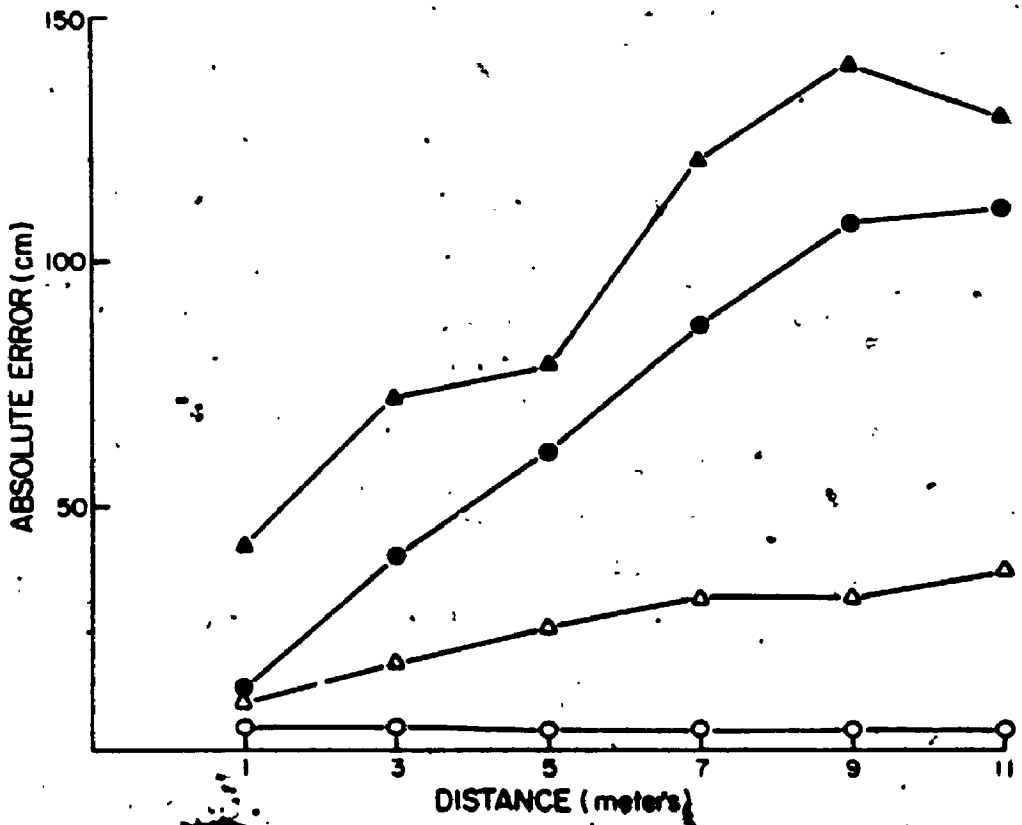

100
50
0
-50
-100
CONSTANT ERROR (cm)
EYES OPEN PERSISTENT
EYES OPEN BRIEF
EYES CLOSED BRIEF
EYES OPEN 180° TURN
TOWARD TARGET

Figure 10. Mean absolute errors (cm; n = 10) for target distances between 1 and 11 m are shown for walks toward a persistent target (open circles), and walks toward a brief target with eyes open (open triangles) and closed (closed circles). Walks in the opposite direction to the target with eyes open are also presented (closed triangles).


150
100
50
ABSOLUTE ERROR (cm)
1
3
5
7
9
11
DISTANCE (meters)

.05) showed a linear increase in absolute errors with increased target distance. Absolute errors in the other two conditions showed linear increases with distance (Eyes closed: $F(1,9) = 13.74$, $p < .005$; Eyes open brief target: $F(1,9) = 15.18$, $p < .005$).

Differences between mean absolute errors depended both on the conditions and target distances examined. For example, when subjects walked toward a brief target they were equally accurate at 1 and 3 m with their eyes open and closed. After 3 m, walks with eyes open toward a brief target were significantly more accurate than walks with eyes closed. When subjects turned and walked in the direction opposite to the target, performance was less accurate at all distances than when they walked with eyes open toward a brief target. Walks when they turned were also less accurate than walks with eyes closed toward the target at all distances except 5 and 11 m. Walks with eyes open toward both a brief and a persistent target were equally accurate at all distances. However, walks with eyes open to a persistent target were more accurate than walks with eyes closed toward a brief target; they were also more accurate than walks with eyes open in the opposite direction to target .

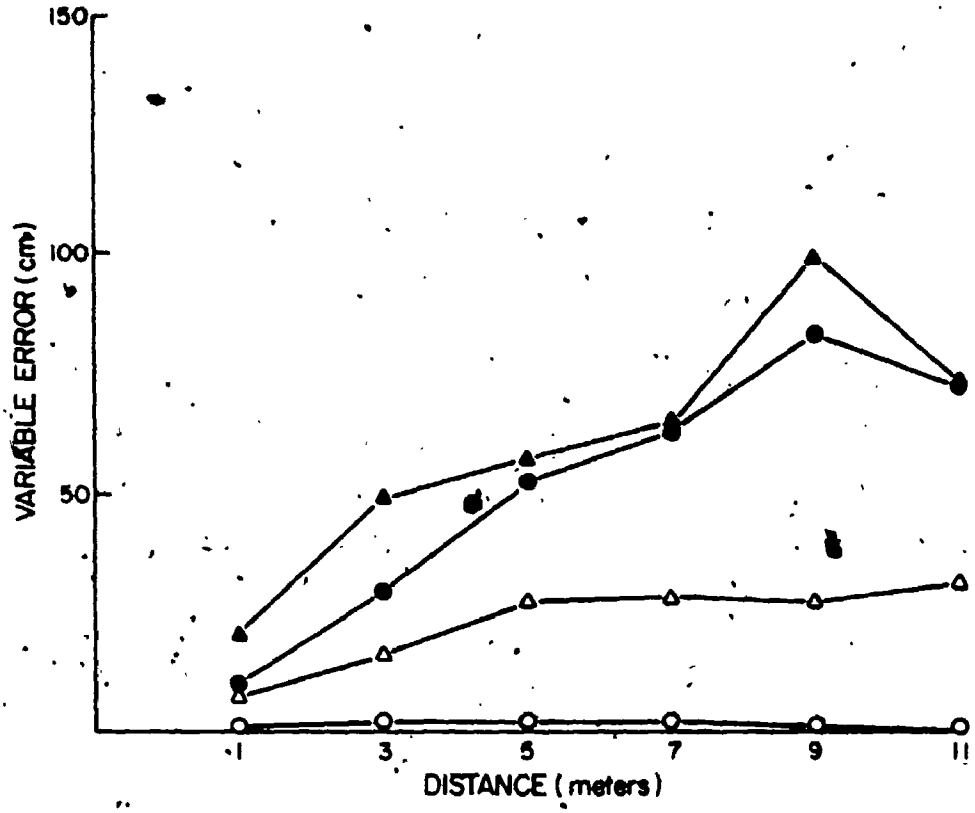
Variable error. Walks with eyes open to a persistent target were less variable than walks in all other conditions. Walks with eyes open toward a target flashed for 200 ms were significantly less variable than walks toward a target with eyes closed. They were also less variable than walks with eyes open in the direction opposite to the target (effect of condition: $F(3,27) = 42.40$, $p < .0001$). Comparisons between the latter two conditions showed that variable error was not

different when subjects walked in the direction of the target with eyes closed and when they turned and walked with eyes open in the opposite direction.

As Figure 11 shows, variable errors increased with distance ($F(5,45) = 21.87$, $p < .0001$), but not equally for all conditions (condition by distance interaction: $F(15,135) = 5.65$, $p < .0001$). For the nearest target, the small variable errors indicated that subjects were consistently walking to a particular location in each of the conditions. However, the location the subjects walked to differed between conditions. Constant errors of overestimation of about 50 cm occurred when subjects turned and walked to the 1 m target. For the 1 m target, errors of only a few cm occurred in the other conditions. So, even though constant errors were significantly different, variable errors were not. By 3 m, performance was significantly more variable when subjects turned and walked than when they walked toward a target flashed for 200 ms. There were no differences, however, between variable errors for walks with eyes closed toward the target and walks with eyes open in the opposite direction. When subjects walked toward a target flashed for 200 ms, walks with eyes open were less variable than walks with eyes closed for targets 5 or more meters away.

The relation between variable error and distance was linear for all conditions (eyes closed walks toward the target: $F(1,9) = 156.99$, $p < .0001$; eyes open walks in the opposite direction: $F(1,9) = 13.86$, $p < .005$; eyes open walks toward the target $F(1,9) = 14.15$, $p < .005$) except for walks with eyes open toward a persistent target ($F(1,9) = 0.06$, $p > .05$). Quadratic components of the relation between variable error and

Figure 11. Mean variable errors (cm; n = 10) over target distances from 1 to 11 m are plotted for walks toward and away from the target. Walks with eyes open to a persistent target (open circles) and a brief target (open triangles) are shown. Walks with eyes closed toward a brief target (closed circles) and walks with eyes open in the direction opposite to target (closed triangles) are also shown.


150
100
50
VARIABLE ERROR (cm)
1
3
5
7
9
11
DISTANCE (meters)

distance most likely resulted from a decrease in variability at 11 m for walks with eyes closed ($F(1,9) = 15.16$, $p < .005$) and eyes open ($F(1,9) = 8.67$, $p < .050$) toward a brief target. The other conditions did not show quadratic components and none of the conditions showed cubic components ($p > .05$).

Discussion

Vision plays a major role in the control of target-directed locomotion, allowing for relatively accurate performance even in the absence of the target. Vision does not guarantee accurate performance, as was demonstrated by the poor performance when subjects walked with their eyes open in the direction opposite to the target. Indeed, the distance to be walked was better remembered in blind walks, suggesting that an additional factor was added by either the 180° rotation of the subject or by the asymmetrical position of the track in the gym. The off-center position of the track made the distance to the wall greater for walks in the direction opposite to the target than it was for walks toward the target. The tendency to overshoot targets when the subjects turned and walked was consistent with the direction of the asymmetry if estimates of target location were proportional to the total distance between the subject and the wall. The position of the track made the normally symmetrical markings on the gym floor asymmetrical. This may have also contributed to the errors of overestimation when the subject turned and walked.

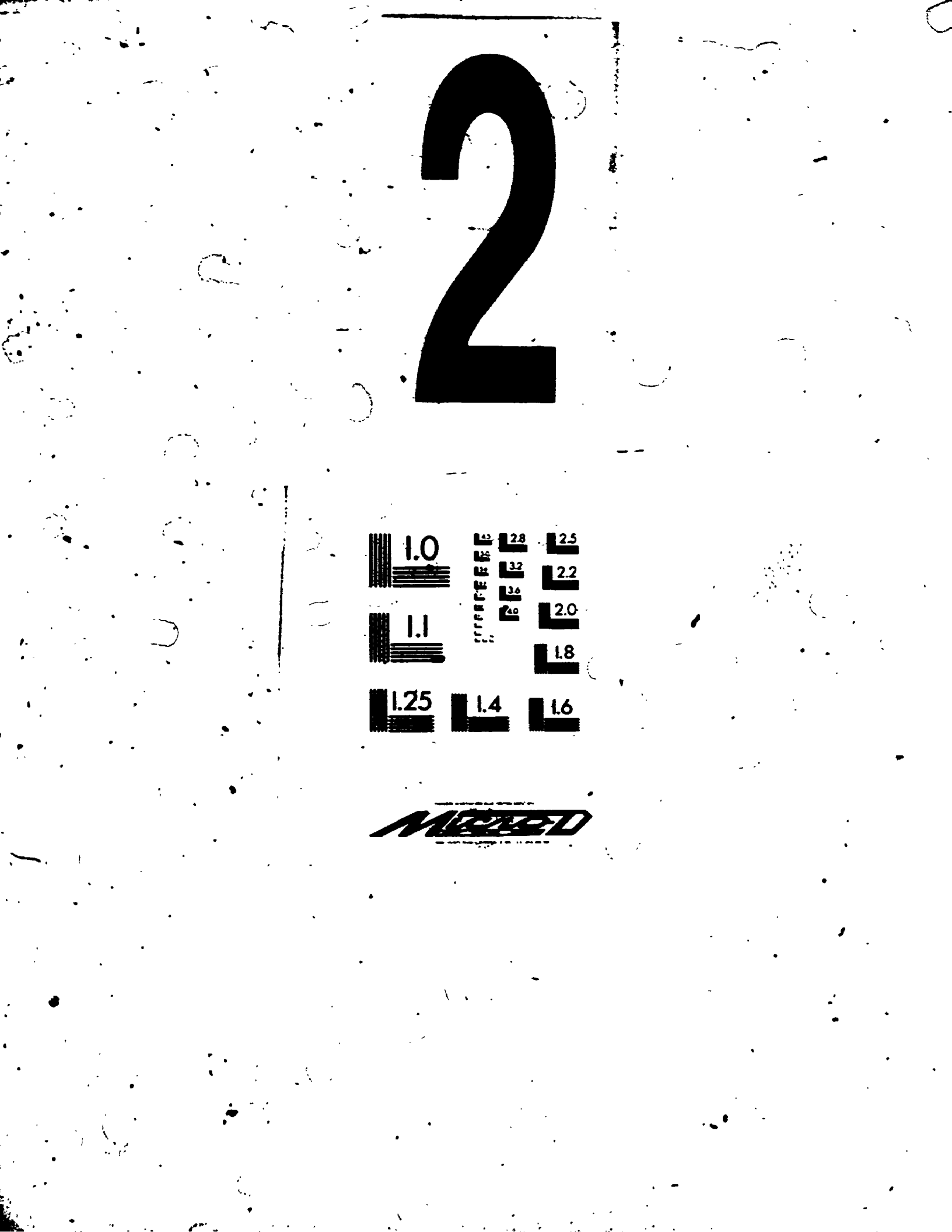
In order to determine whether the mental remapping of the target or the asymmetry in the physical environment was responsible for the

overshoot, the following experiment was performed. In this experiment, subjects walked with eyes closed and with eyes open in the direction opposite to the target. The possible contribution of asymmetries in space was eliminated by keeping the distance to the wall the same in both directions and by presenting the target in one direction to half the subjects and in the opposite direction to the other subjects. It was expected, that if the pattern of errors found in the previous study was produced by the asymmetry of space, no overshoot would be present since space was now symmetrical. If the effect was due to erroneous visual information (for example, cues present in the environment) a difference would be expected between walks with and without visual feedback. The nature of these differences could not be predicted, however, since there was no a priori reason to believe any cues present in the corridor used as an experimental setting would cause a selective overshoot or undershoot of target distance. Finally, if the effect resulted from the rotation of the subject then both walks with eyes open and with eyes closed would show the same tendency to overestimate target distance.

EXPERIMENT 6

Method

Nine right-handed paid volunteers (4 male and 5 female) with normal or corrected vision and ranging in age from 19 to 26 years (mean = 21.11, s.d. = 2.37) walked to a target placed at various distances in a corridor. The target and hallway were the same as those previously described in Experiment 1 of chapter 1. The hallway had been divided


2
1.0
1.1
1.25
1.4
1.6
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
1.8

into two adjacent 14.8 m long sections by a pair of start-lines 60 cm apart. As Figure 12 shows, the two sections of the hallway backed onto each other. The target was presented in one section. The subjects walked toward the target in some conditions. In other conditions, they walked down the other section of the hallway in the direction opposite to the target. The section of the hallway used to present the target was changed after 5 subjects. This change controlled for any subtle asymmetries that may have been present in the two parts of the hallway. Subjects walked to a target at 3, 6, 9, or 12 m three times in each of 4 conditions. One trial at each distance was presented in random order before a second trial was presented at a given distance. The conditions, which were presented in a counter-balanced order were:

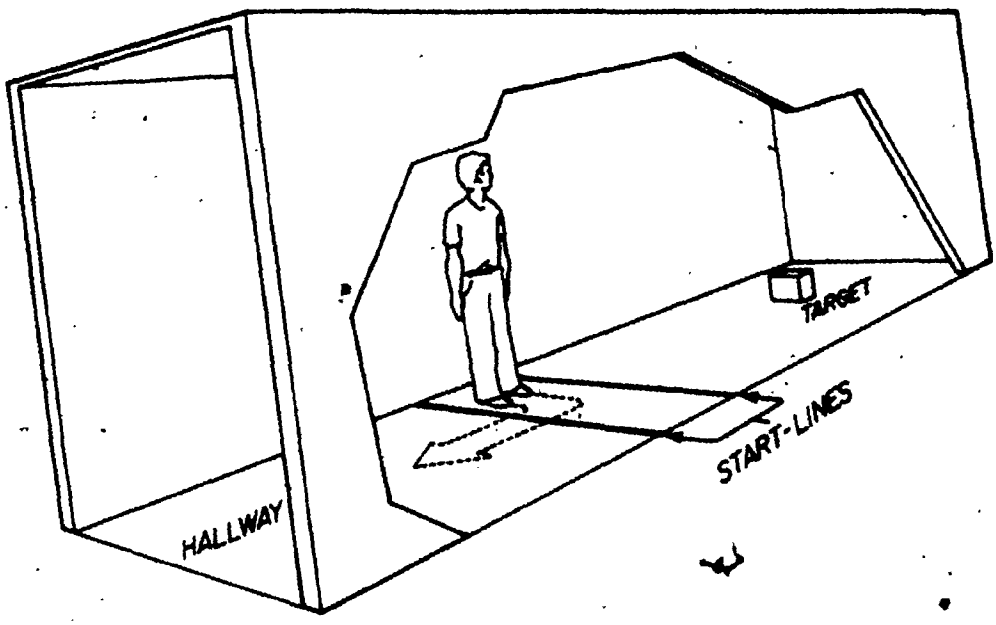
Condition 1. Walks with eyes closed toward the target.

Condition 2. Walks with eyes closed in the direction opposite to the target.

Condition 3. Walks with eyes open in the direction opposite to the target.

For all conditions, when subjects viewed the target they stood between the start-lines facing the wall (perpendicular to the direction they walked) and looked at the target over their shoulder. Therefore, on all trials, subjects had to turn their bodies through 90° before they walked. This viewing position was used in an attempt to hold body-rotation constant across conditions. It should be noted, however, that when subjects walked in the direction of the target their head and eyes rotated very little, but when they walked in the opposite direction to the target their head and eyes made an approximately 180°

Figure 12. A schematic of the experimental setting showing a subject standing between the start-lines looking at the target over his/her shoulder. The arrow indicates the direction the subject turned when he/she walked in the opposite direction to the target. The portion of the hallway used to present the target and, therefore, the direction the subject turned was reversed for half the subjects.


TARGET
START-LINES
HALLWAY

rotation. On all blind walks, subjects closed their eyes before they turned. This ensured that subjects did not simply choose a new location using vision. The subject's accuracy depended on information they obtained while viewing the target.

Prior to beginning the experiment, subjects were given training walking to targets (see Experiment 3 of the Short-term memory section for details). More practice was given between the second and third conditions following a short break.

Data analysis

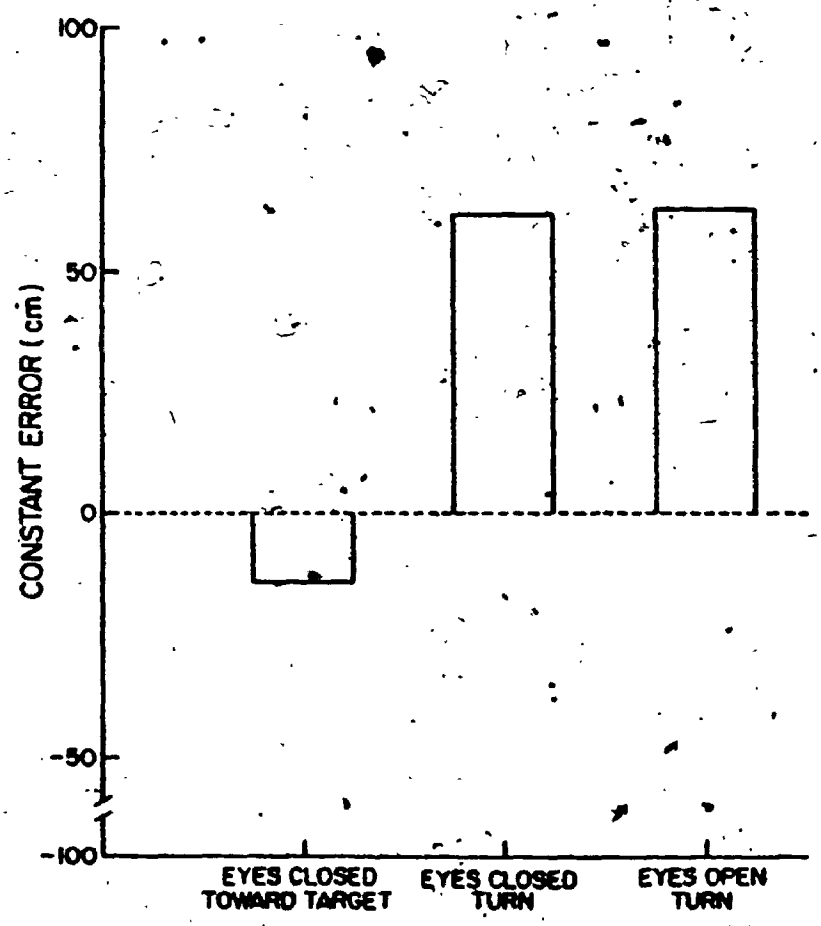
The distance the subjects walked was measured on each trial. Constant, absolute, and variable errors were calculated for each subject. Constant, absolute, and variable errors scores were each subjected to a 3 (condition) X 4 (distance) repeated measures analysis of variance.

Results

The effects of rotation

Constant error. On walks in the opposite direction to the target, the distance to all targets was overestimated (see Figure 13). The magnitude of overshoots was the same whether the subjects walked with their eyes open or closed, but was significantly different from constant errors made when the subjects walked toward the target (effect of condition: $F(2,14) = 4.88$, $p < .05$). For walks toward the target, there was a tendency to underestimate the target distance for the more distant targets. This was indicated as a significant effect of distance on constant error ($F(3,21) = 4.30$, $p < .05$). Overshoots made

Figure 13. Mean constant errors (cm; n = 9) collapsed over all target distances are shown for walks in the direction of target with eyes closed and for walks in the direction opposite to the target with eyes open and closed.


100
50
0
-50
-100
CONSTANT ERROR (cm)
EYES CLOSED TOWARD TARGET
EYES CLOSED TURN
EYES OPEN TURN

when the subjects turned and walked in the direction opposite to the target did not increase with increasing target distance.

Absolute error. On all walks in the opposite direction to the target, larger absolute errors were made than when the subjects walked toward the target (effect of condition: $F(2,14) = 6.57$, $p < .05$). As is shown in Figure 14, when the subjects walked in the opposite direction to the target, mean absolute errors were the same whether vision was present or not.

There was a significant increase in absolute error with distance in all conditions shown in Figure 14 ($F(3,21) = 6.18$, $p < .005$). When the subjects walked in the opposite direction to the target, absolute errors at 3 m were surprisingly large, often exceeding a meter. These errors tended to level off after 6 m especially for walks with eyes open. There was a linear relation between absolute errors and target distance for walks toward the target ($F(1,8) = 18.86$, $p < .005$), but not for walks in the opposite direction (eyes open: $F(1,8) = 1.74$, $p > .05$; eyes closed: $F(1,8) = 1.80$, $p > .05$). None of the conditions showed cubic or quadratic components.

Variable error. In spite of the fact that there was only a trend for condition to affect variable error ($F(2,16) = 3.25$, $p = .065$), a number of consistencies are apparent in the data shown in Figure 15. The function describing the relation between variable error and distance for walks with eyes closed in the direction opposite to the target lay above the function for walks with eyes closed toward the target. On the other hand, variable errors for walks in the opposite direction with eyes open were very similar to errors made with eyes

Figure 14. Mean absolute errors (cm; n = 9) over all target distances are shown for walks toward the target with eyes closed (closed circles). Errors are also shown for walks in the opposite direction to the target with eyes open (closed triangles) and closed (open circles).

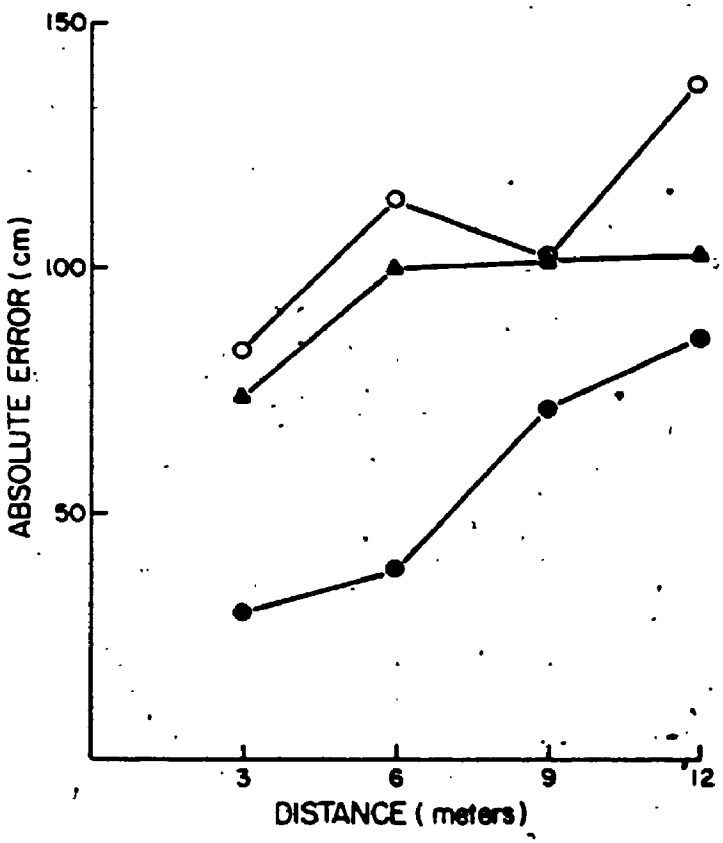
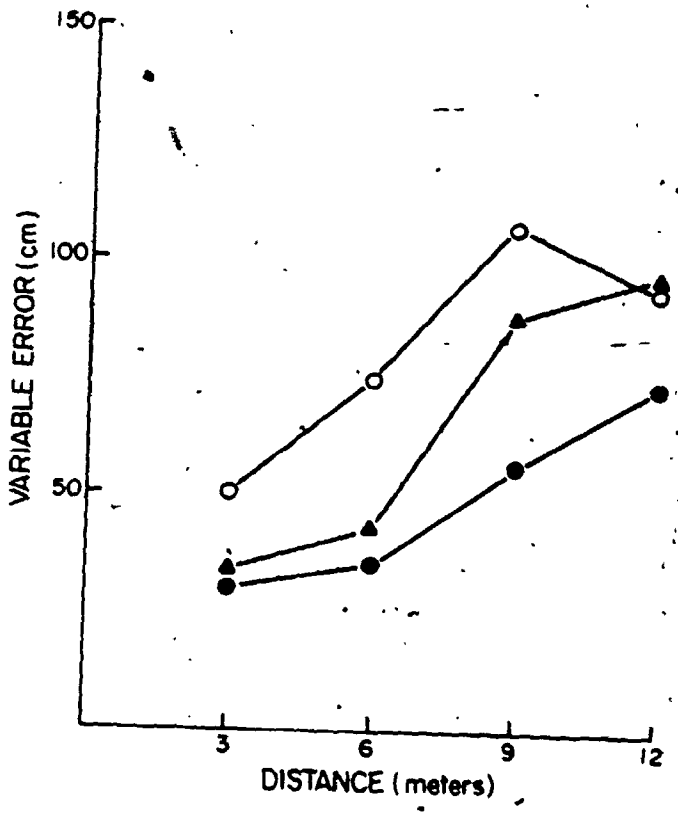

150
100
50
ABSOLUTE ERROR (cm)
3
6
9
12
DISTANCE (meters)

Figure 15. Mean variable errors (cm; n = 9) over all target distances are shown for walks toward the target with eyes closed (closed circles). Walks with eyes open (closed triangles) and eyes closed (open circles) in the opposite direction to the target are also presented.


150
100
50
VARIABLE ERROR (cm)
3
6
9
12
DISTANCE (meters)

closed toward the target at 3 and 6 m. At 9 m, errors on the eyes open walks increased rapidly attaining the same level as variable errors made when subjects turned and walked with their eyes closed.

Variable errors increased with distance in all conditions ($F(3,24) = 10.73$, $p < .005$). A linear relation existed between variable errors and distance for walks with eyes open in the opposite direction to the target ($F(1,8) = 10.88$, $p < .05$). Walks with eyes closed toward the target ($F(1,8) = 5.11$, $p = .054$) and walks in the opposite direction to the target ($F(1,8) = 3.19$, $p = .112$) both showed trends for a linear relation between variable error and distance.

Discussion

When subjects were required to walk in the direction opposite to the target, they overestimated the distance to all targets for walks both with and without visual feedback. The effect of overestimation was pervasive. For walks with eyes open, 81% of the errors were overestimations. For walks with eyes closed, 78% were errors of overestimation. If subjects were underestimating the distance to the far target during viewing, then errors of underestimation might have reduced the overshoot produced by the rotation. Absolute errors may have leveled off at far targets because they reflected the sum of perceptual underestimation and rotation induced-overestimation.

When subjects walked in the direction opposite to the target, variable errors depended on both target distance and on whether subjects walked with their eyes open or closed. At near distances (3 and 6 m targets), a dissociation between variable errors for walks with

eyes open and closed suggests that subjects could use information available through vision to choose the same final position on many walks. The consistency in their performance occurred in spite of a substantial overestimations of the distance to be walked. At 9 m, variable error on walks with eyes open increased abruptly to the same level as that found on walks with eyes closed, indicating that vision could no longer be used to supply subjects with a reliable aiming point. For walks with eyes closed, no opportunity was available to look at the hallway before walking. Thus, a new aiming point could not be chosen, as it could when subjects walked with eyes open.

CONCLUDING REMARKS

Accurate locomotion directed to targets in the immediate environment has been shown, by the present investigations, to be affected by a number of factors including the availability of visual feedback, target distance, and the direction the subject is required to walk.

Visual feedback

The results of the present experiments suggest that vision can be used to choose a relatively accurate substitute for the target when contextual information contributes to the choice. Vision of the environment surrounding a target, in the absence of the target itself, was associated with more accurate performance than either walks without visual feedback or walks where the information provided by vision did not relate directly to the original perception. Relevant contextual information, in the absence of the target did not, however, substitute

for full visual feedback. Walks with eyes open to a target flashed for 200 ms were not as accurate as walks where the target remained visible. At best, the terminal position of walks toward a target that has gone out of view only approximates the target location.

The accuracy that Thomson (1980, 1983) reported for targets up to 9 m or 8 s away was not duplicated here, even in the instance where additional contextual information was provided by vision. This finding makes Thomson's claim that walks without visual feedback can be as accurate as those with full visual feedback even more puzzling. Further, the data presented here confirm that by training his subjects Thomson achieved more than simply acclimatizing them to the unfamiliar task of walking with their eyes closed (Thomson, 1986). Indeed, it appears that Thomson's subjects had more information about the precise location of the target while walking with their eyes closed than subjects in the present experiment had walking with their eyes open to a target that had just gone out of view.

The effects of rotation

Since errors of overestimation occurred on both walks with and without visual feedback at all target distances, it seems reasonable to suggest that the internal representation of the target location was altered by the rotation. One limitation of the present investigations was that effects due to rotation of the head and eyes could not be dissociated from effects that might have been due to a remapping of the target and/or rotating the space containing the target onto the new environment. It seems less likely that the overestimation errors were due to rotation of the head and eyes, since eliminating rotation of the

body in the second experiment did not appear to have any effect on the overestimation. Evidence from the two experiments presented here suggests that when one is required to perform the mental act of transposing the layout of the environment that one has viewed onto the space "behind the head" (Attneave & Farrar, 1977), a constant error of overestimation occurs. The results also seem to indicate that either target distance per se was not coded or that the concept of target distance was tied to the environment in which the perception took place. It was surprising that information available on visually guided walks did not affect the tendency to overestimate target distance. In theory, vision could have been used to compare the distance traversed to the distance perceived before the subject turned. It seems reasonable, therefore, to suggest that the internal representation or short-term memory of the target location was altered by the rotation.

Future perspectives

The findings reported here lead to a number of unanswered questions regarding the nature of the representation of spatial layout and/or target distance. First, was the effect of rotation dependent on the knowledge that a transposition was necessary? If subjects believed they were oriented toward the target when they were not, would the error pattern reflect the actual orientation or the subjective orientation of the subject? I predict that if subjects believed they were oriented in the position in which they had originally perceived the target, errors of overestimation would not occur.

Second, if subjects turned 360°, would the same effect of rotation occur? Complete rotations would also allow a dissociation

between the effects of rotation of the head, eyes, and body and the effects of remapping an object or rotating space. A 360^{o} rotation would not be expected to produce errors of overestimation, if the effect was due to the remapping of a previously viewed space onto the space that was behind your head at the time of the perception. Once subjects were oriented in their original position, remapping would not be necessary and locomotion could proceed as before.

Third, deviations from the original target position of up to about 90^{o} in either direction would require a remapping of the target to a new location in space that was in front of the subject. Rotations of more than 90^{o} would mean moving the target into space that the subject was not able to see at the time the target was perceived. Would all rotations of more than approximately 90^{o}, but less than about 180^{o} produce errors of overestimation? Finally, would the direction of rotation alter the effect? Would, for example, a rotation of 315^{o} produce the same effects as a rotation of -45^{o}?

Further investigation is necessary to determine how visual information about target locations and/or target distances is used to structure the immediate environment. Once we begin to understand what information is encoded when a subject walks to a target in his/her immediate surroundings, we will be in a better position to assess the relation between performance in a relatively simple environment and performance in a more complex environment.

CHAPTER 3

THE RELATION BETWEEN LOCOMOTOR ACCURACY, PERCEPTION OF TARGET DISTANCE, AND SPATIAL ABILITY

I have suggested that the ability to walk accurately to a nearby target depends on accuracy in perceiving the distance to the target, accuracy in translating the perception into action, and accuracy in carrying out the action. Moreover, if the target goes out of view, locomotor accuracy should depend on the accuracy of memory for the location of the target. In the following experiment, I examined the relationship between perceptual and locomotor accuracy. Perceptual and motor errors were examined in two different tasks, not within the same perceptual-motor task as others have done (Woodworth, 1899). In the perceptual task, subjects estimated the number of units they thought it was to a nearby target, but did not walk to the target. In the locomotor task, subjects walked to a nearby target with their eyes closed. Because perception of target distance was assumed to be the first step in both tasks, similarities in performance could be attributed to a common source: perceptual processes.

In the following experiment, spatial ability was also examined in relation to perceptual and locomotor accuracy. The ability to act in the environment and to keep track of one's position relative to objects within the environment (McGee, 1979) is thought to be tapped by paper and pencil tests of spatial ability, although few investigators have examined this relationship directly. There is a small amount of experimental evidence to suggest that spatial ability, as measured by

such written tests, relates to accuracy on visuomotor tasks (Kolakowski & Malina, 1974; Jardine & Martin, 1983; Watson, 1985). It was expected, therefore, that individual differences in spatial ability would relate to individual differences in locomotor accuracy.

Perception and performance

The precise 'metric' of visual space remains a subject of controversy. It has been shown, however, that errors in perception vary as a function of target distance (Gibson & Bergman, 1954; Harway, 1963; Wagner, 1985). Both constant errors (Harway, 1963) and absolute errors (Gibson & Bergman, 1954) increase with target distance. Motor errors also increase with increasing target distance. For example, errors in non-visually guided limb movements increase as movement distance increases (Laabs & Simmons, 1981; Posner, 1967; Woodworth, 1899). The relation between perceptual errors and motor errors has received little attention since Woodworth made his investigation of perceptual-motor skills at the turn of the century.

Fullerton and Cattell (1882, cited in Woodworth, 1899) suggested that when a limb movement was reproduced, the larger source of error was perceptual. This finding was replicated by Woodworth (1899) who examined the relative contribution of perceptual and motor errors to the accurate reproduction of line length. He postulated that perceptual and motor errors could be examined independently by varying the distance between a standard line and the reproduction line. According to Woodworth, when the stimulus and reproduction lines were close together perceptual error was minimized, while motor error was reduced by drawing the lines on top of each other. When the distance

between the two lines was increased, both perceptual and motor errors were present. Generally, errors in perception tended to exceed motor errors. However, the sum of independently obtained perceptual and motor errors was consistently smaller than when both perceptual and motor errors occurred on the same reproduction. The additional error was postulated to result from translating perception into action.

The perceptual task used here, involved estimation of the number of units to a target and was similar to the task used by Gibson and Bergman (1954). In an earlier chapter, it was reported that subjects spontaneously adopt a pace-estimation strategy on the locomotion task. Ninety percent of the subjects, in the present experiment, estimated the number of paces to the target on the locomotion task (these data were previously presented in Experiment 2 of chapter 1). This does not necessarily imply, however, that information about target distance is translated into unit measures in the 'real' world. In both tasks used here, a conversion of distance into units took place. On the locomotion task, this conversion was spontaneous, while on the perceptual task, it was an experimental requirement. Conversion of target distance into subjective or objective units may have introduced a source of error in addition to the perceptual and motor errors already discussed.

Increasing the distance to a target for both motor and perceptual tasks has been found to result in distinctive constant, absolute, and variable error patterns. The pattern of constant errors known as the range effect has been reported in both distance perception and movement magnitude experiments (Poulton, 1975). Probable range effects were

found on the target-directed locomotion task used here (chapter 1). The range effect is thought to result from perceptual processes (Laabs, 1979; Laabs & Simmons, 1981). Thus, a range effect was expected on both the locomotor and perceptual tasks used in the present experiment. Moreover, constant errors should be related on the perceptual and locomotor tasks if a similar range of distances is used on both tasks. An effect of increasing target distance would be anticipated on both the perceptual (Gibson & Bergman, 1954; Harway, 1963; Wagner, 1985) and the motor tasks (Posner, 1967). It was expected that performance on tasks of distance perception and target-directed locomotion would be strongly related, if the common source of error was perceptual. If as Woodward (1899) suggests, perceptual errors are enhanced by translating a perception into action, then variable errors would be expected to be larger on the locomotor task. On the other hand, constant errors, which are thought to reflect perceptual processes, should not differ. Of course, this simplistic view does not take into account errors that might be specific to the individual tasks.

Spatial ability

The ability to acquire knowlege about the relations between the parts of the environment, including ourselves, may be considered a basic ability underlying spatial performance. Many different human behaviors are assumed under the spatial-ability label. Some of these behaviors seem far removed from the abilities that allowed our ancestors to survive and reproduce. In early man, tracking and hunting game, locating water and edible plants, and remembering the routes to these food sources would have been essential to survival. Our

ancestors, at least in the hunter-gatherer societies, would have had great demands put on a well-developed sense of spatial ability (Kolakowski and Malina, 1974).

Factor analytic studies in the 1930s revealed that general intelligence could be divided into a number of separate abilities (see Scarr & Carter-Saltzman, 1982 for a review). Spatial ability, established as one cognitive ability, was later subdivided into visualization and orientation factors (see Harris, 1978, 1981 and McGee, 1979 for a review of spatial abilities). In the literature, the definitions of these factors have varied (McGee, 1979). McGee, however, notes that most definitions of the visualization factor involve the rotation or manipulation of parts of objects and whole objects. For example, a well-known test of visualization involves the mental folding and unfolding of drawn stimulus items to determine which of several alternatives is formed by the completed figure (French, Ekstrom & Price, 1963). According to McGee, spatial orientation has been described as the ability to understand the relationship between objects in an array, including one's self, and maintain that understanding when the arrangement of the array changes. For example, the orientation factor has been tested by the ability to determine the new heading of a boat in a drawn scene when the background scenery is changed (Guilford & Zimmerman, 1953). McGee (1979) suggests that both visualization and orientation require short-term visual memory and mental rotation. Visualization requires serial operations, such as the mental unfolding of a piece of paper, in addition to the rotation.

Performance on written tests of spatial ability have been related to a number of other skills and abilities. Although most tests of spatial ability are performed with objects and scenes represented by pictures, performance on these tests are thought to relate to spatial abilities in the 'real' 3-dimensional world. McGee (1979), in reviewing the predictive validity of tests of spatial ability, reports ample evidence that scores on spatial-ability tests can be used to predict performance in areas such as mathematics, architecture, and mechanical drawing, as well as success in vocational-technical courses. Spatial orientation has been found to be related to map reading and sense of direction (McGee, 1979).

Evidence relating performance on written tests of spatial ability to basic visuomotor behaviors (throwing: Jardine & Martin, 1983; Kolakowski & Malina, 1974; Watson, 1985) is much more limited. Kolakowski and Malina (1974) related throwing accuracy to spatial skills in a sample of 67 boys aged 14 to 16 years. As absolute vertical throwing errors increased, scores on the Primary Mental Abilities (PMA) test decreased. In other words, subjects with poor spatial skills, as measured by the PMA tests, also threw inaccurately. These investigators suggest that a relation between performance on written tests of spatial ability and accuracy in visuomotor tasks may have a common origin in man's hunting heritage. Although Kolakowski and Malina do not examine the relation between performance on written tests of spatial ability and hunting ability directly, they suggest that selection pressures would have favored individuals with good visuomotor and spatial abilities -- skilled hunters would have been

more likely to survive than less skilled ones.

Jardine and Martin (1983) recently replicated the earlier finding, also reporting a significant relation between spatial ability and throwing accuracy. A test of direction sense (a revised version of the Money road map test) was most often found to correlate with throwing accuracy. Subjects who performed poorly on the Road map test also threw least accurately. The fact that a good sense of direction correlated with throwing accuracy offered some support for the notion, put forward by Kolakowski and Malina (1974), that superior spatial ability had survival value for early man. Their findings also indicated that some spatial tests, which appear to relate to a subject's ability to maintain his/her orientation in the environment, may show a stronger relation with visuomotor behaviors than other tests of spatial ability (Cube comparisons and Paper folding tests showed fewer correlations with throwing accuracy) which do not appear to relate to many environmently oriented behaviors. In another study, hammering and dart throwing accuracy showed correlations with the Money road map test, while only dart throwing accuracy related to performance on the Paper folding test (Watson, 1985).

Spatial ability has also been postulated to relate to way-finding in the environment (McGee, 1979). Eskimos, traditionally nomadic hunters, had superior performance on written tests of spatial ability compared to Temne Africans, a sedentary agrarian tribe (Berry, 1966). Although way-finding ability was not specifically tested by Berry, differences in spatial ability were assumed to have resulted from the spatially demanding lifestyle of the Eskimos. For nomadic tribes,

selection pressures would have favored individuals with superior spatial ability. No such pressure would have acted on more sedentary groups of individuals. Therefore, superior spatial abilities, including way-finding skills, would not be predicted to be a general characteristic of sedentary groups like the Temne. Nevertheless, spatial ability would still be expected to relate to way-finding ability. Recently, Walsh, Krauss, and Regnier (1981) reported significant correlations between knowledge of the location of neighborhood landmarks and standard written tests of spatial ability (PMA) in a sample of 31 elderly persons.

Inasmuch as the target-directed locomotion examined here was a visuomotor behavior, it was expected that accuracy on the locomotion task would be related to performance on written tests of spatial ability. Since visuomotor tasks, which have been shown to relate to spatial ability, involve both a perceptual and motor component, it is also possible that perceptual performance by itself would relate to spatial ability. Finally, performance on the perceptual task was also predicted to relate to performance on the target-directed locomotion task.

Method

Twenty (10 male and 10 female) right-handed paid volunteers (mean = 22.85, s.d. = 3.22 years) with normal or corrected vision served as subjects.

Tests of spatial ability

1. Money road map test (Money, Alexander, & Walker, 1965). In

this test, subjects mentally followed a route marked on a schematic city street map. At each corner along the route of this imaginary walk, subjects indicated whether they would turn to the right or the left as they walked along the route to its termination. The original version of the test did not have a time-limit. Following the suggestion of Jardine and Martin (1983), a 1-minute time-limit was imposed. The spatial orientation factor is thought to be sampled by this test (Harris, 1981; McGee, 1979). The score was the number of correct responses within the time-limit.

ii. Paper folding test (French, et al., 1963). Drawings demonstrating the folding (either 2 or 3 folds) of a sheet of paper, which when folded has a hole punched in it, were presented in this task. The subject marked which of five alternatives represented the arrangement of holes that would be found once the paper was unfolded again. The test was divided into two 3-minute parts of 10 items each. The visualization factor is thought to be sampled by this test. Scores were obtained by subtracting one-fifth the number of incorrect responses from the number of correct responses. Subjects were warned in the written instructions, provided with the test, that guessing would be penalized.

iii. Cube comparisons (French, et al., 1963). In this test, subjects were presented with two drawings of 3-dimensional cubes, with front, right side, and top surfaces showing. There were different letters or symbols on each of the cube's six surfaces. The subject judged whether the two drawings could be rotated versions of the same cube or whether they were different cubes. The test was presented in

two 3-minute parts. Each part consisted of 21 items. This test is thought to sample the orientation factor. Scores were obtained by subtracting the number of incorrect responses from the number of correct responses. Again, subjects were aware that guessing would be penalized.

Locomotion task

Subjects walked with eyes closed to a target placed at distances up to 15 m away in a 30 m long corridor. The details of the locomotion task and error analyses were presented previously in the method section of Experiment 2 in chapter 1. Data from the 2 and 4 s delay conditions were not included in the present analyses.

Estimation of target distance

Following the completion of the locomotion task, subjects were given a unit measure. This measure was a length of wood 5 cm wide and 63 cm long. The subjects stood at the start-line of the same corridor used on the locomotion experiment and estimated the number of units the target was away. Partial units were allowed. Subjects could, for example, say that the target was '4 and a quarter units' away. The target was placed in a random order at the same distances as those used in the locomotion experiment. Five trials were given at each distance. Although subjects held the length of wood in their hands and comparison was possible, prolonged calculations were discouraged. A non-standard unit was used in order to eliminate any possible effect that selective experience with a common measuring device, such as a meter stick, might have had. For each target distance, constant, variable, and absolute errors were calculated after the number of units reported by the

subject was transformed into distance.

The tests of spatial ability, which were presented in a counter-balanced order, were administered first, followed by the locomotion task. The perceptual task was administered last.

Data analysis

The perception and locomotion data were examined for similarities and differences. Differences in performance accuracy between the two tasks were examined by subjecting the constant, variable, and absolute errors each to a 2 (condition) X 5 (distance) repeated measures analysis of variance. Significant effects were further evaluated using post hoc LSD tests.

Pearson product-moment correlations were performed to investigate similarities between performance on the two tasks. Mean errors (collapsed over all distances) on the perceptual task were compared with mean errors on the locomotor task. The relationship between errors on the perceptual and locomotor tasks was also examined at two of the target distances, 3 m and 9 m. A near and a far target distance were chosen because errors had been found to increase with target distance. Mean errors (collapsed over distance) would not have reflected changes in performance that might have been associated with different levels of difficulty. The 9 m target was chosen as the far distance because variable error levelled off at the 12 m target and decreased at the 15 m target in the present experiment. Perceptual and locomotor errors at these selected target distances were also examined in relation to scores on the three spatial tests.

Results

Locomotion and perceptual tasks

Constant error. Overall, constant errors were not significantly different for the perceptual and locomotion conditions (see Figure 16; $F(1,19) = 1.89$, $p = .185$). Target distance did not affect constant errors (distance: $F(4,76) = 1.68$, $p = .164$; condition by distance interaction: $F(4,76) = 1.61$, $p = .181$).

Absolute error. Absolute errors were significantly larger on the perceptual task than on the locomotion task with a mean of 1.98 m as compared to 1.13 m (condition: $F(1,19) = 9.39$, $p < .01$). As is shown in Figure 17, absolute errors increased with distance in both conditions (distance: $F(4,76) = 35.71$, $p < .0001$; condition by distance interaction: $F(4,76) = 1.92$, $p = .126$). Differences between locomotor and perceptual errors were significant beyond 6 m (LSD, $df = 56$, $p < .05$). The relation between target distance and absolute error was linear for both the locomotor ($F(1,19) = 107.74$, $p < .0001$) and perceptual ($F(1,19) = 19.92$, $p < .001$) tasks.

Variable error. Mean variable errors were the same in the perceptual and the locomotion conditions (condition: $F(1,19) = .267$, $p > .05$). Variable error increased with distance on both tasks ($F(4,76) = 27.73$, $p < .0001$). But as can be seen in Figure 18, the effect of target distance was not the same in the two tasks (condition by distance interaction: $F(4,76) = 4.52$, $p < .005$). At 9 m, perceptual error exceeded locomotor error (LSD: $df = 81$, $p < .05$), while at 15 m error on the perceptual task was lower than it was on the locomotor task (LSD: $df = 81$, $p < .05$). Variable errors increased in a linear

Figure 16. Mean constant errors and standard deviations (cm) for subjects (n = 20) performing the locomotor task (closed circles) and the perceptual task (closed triangles) for target distances between 3 and 15 m.

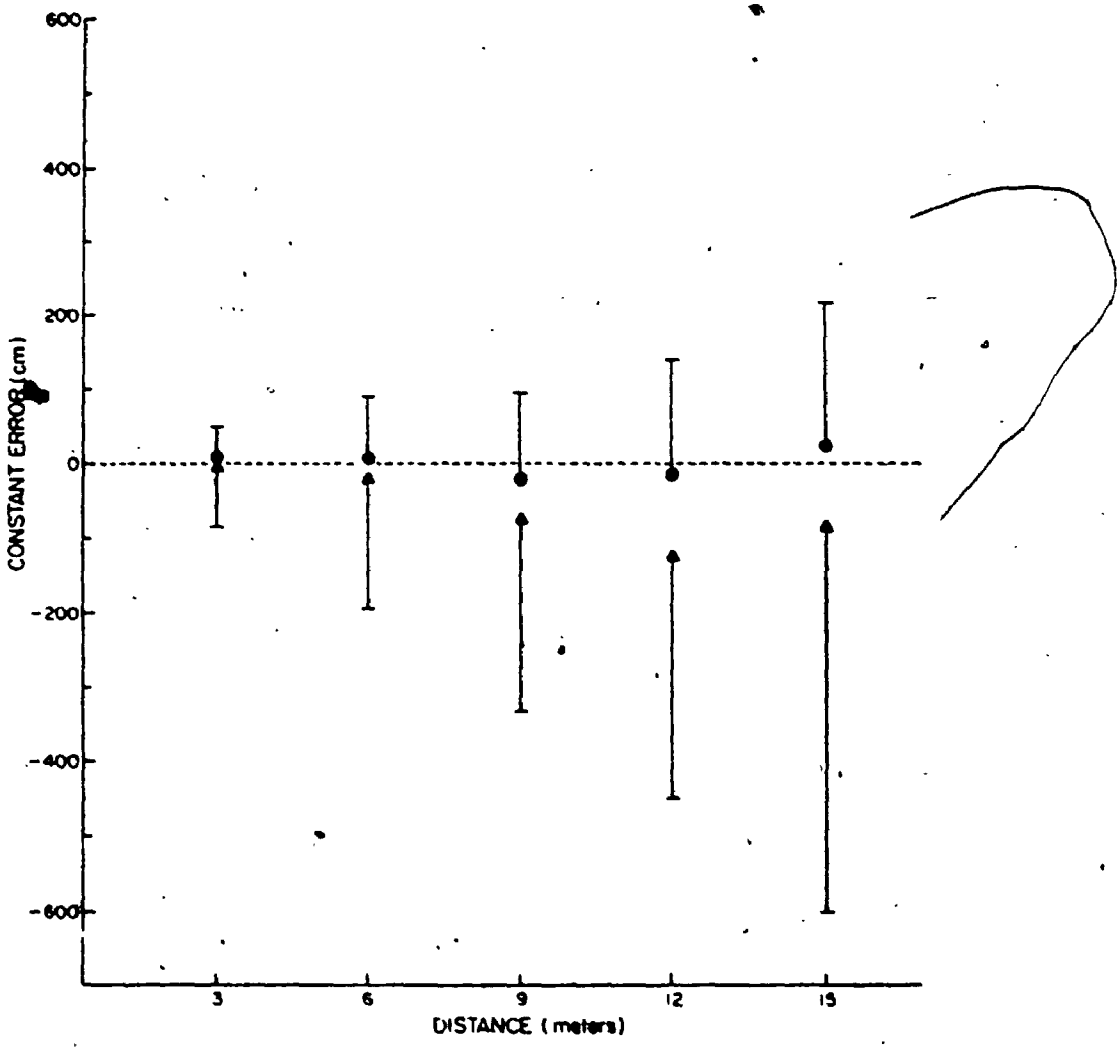

600
400
200
0
-200
-400
-600
CONSTANT ERROR (cm)
3
6
9
12
15
DISTANCE (meters)

Figure 17. Mean absolute errors (cm) for walks with eyes closed (closed circles) and for estimates of the number of units to the target (closed triangles) for distances up to 15 m away (n = 20).

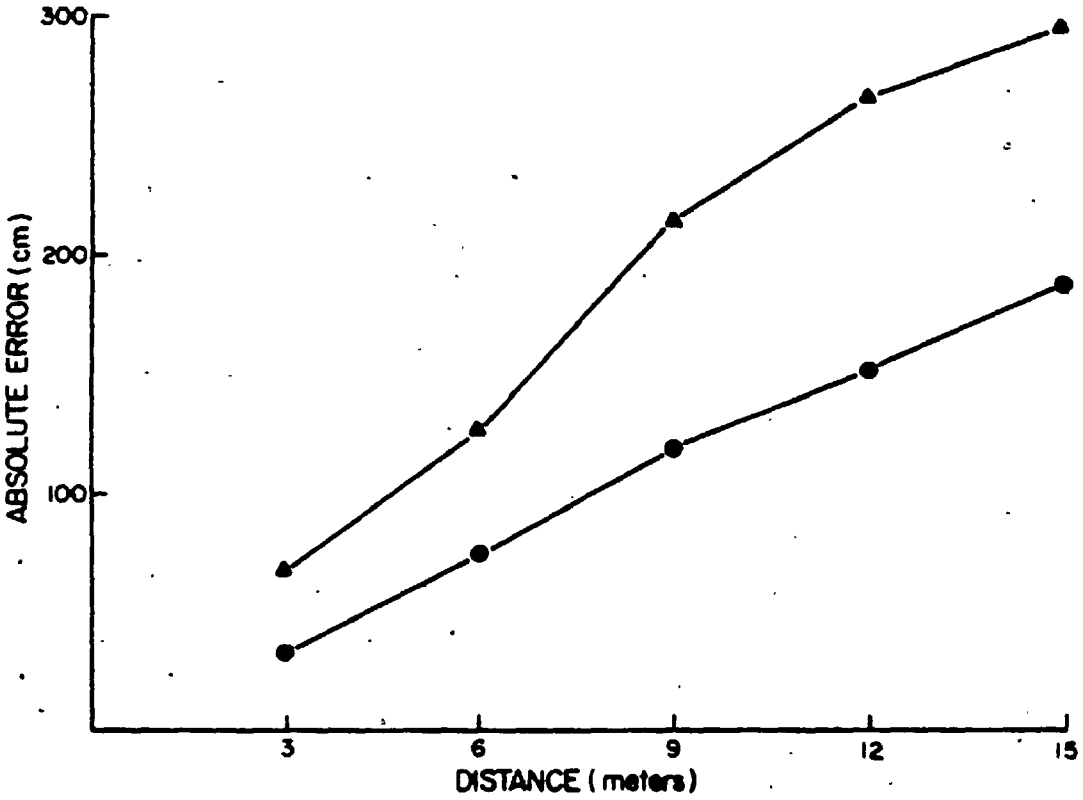
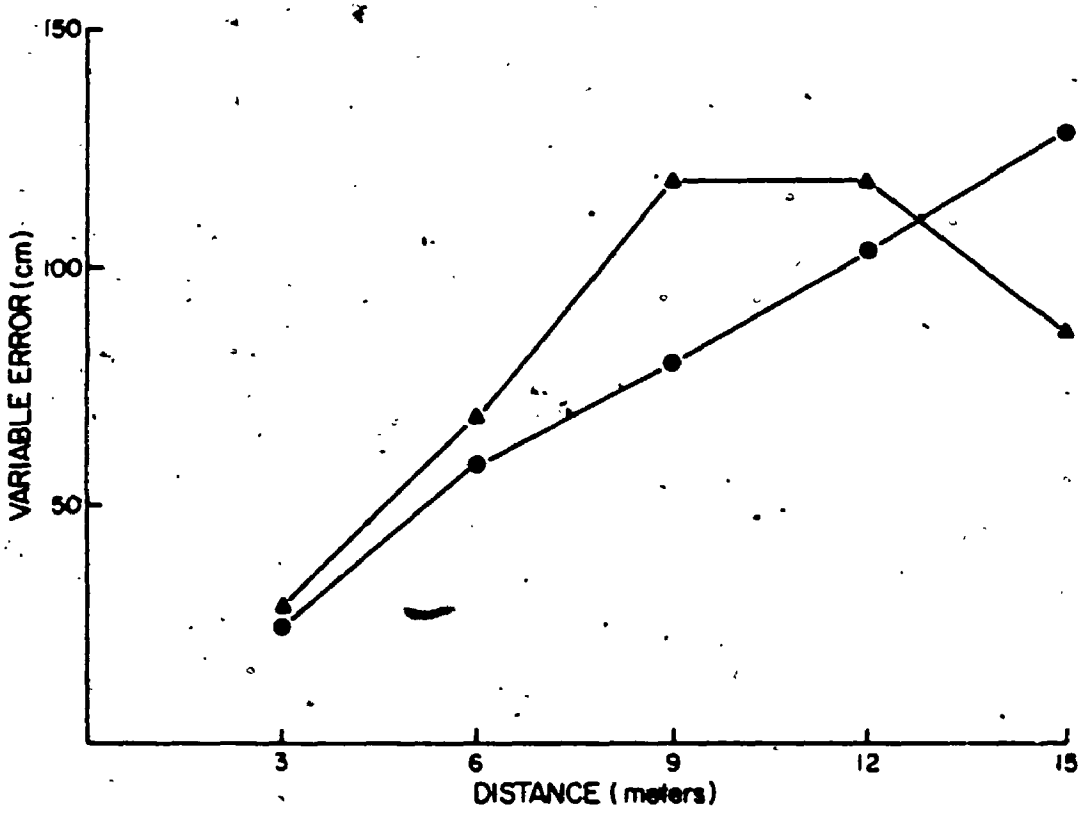

300
200
100
ABSOLUTE ERROR (cm)
3
6
9
12
15
DISTANCE (meters)

Figure 18. Mean variable errors (cm) for walks with eyes closed (closed circles) and for estimates of the number of units to the target (closed triangles) for distances up to 15 m away (n = 20) are shown.


150
100
50
VARIABLE ERROR (cm)
3
6
9
12
15
DISTANCE (meters)

fashion in both tasks (locomotor: $F(1,19) = 54.84$, $p < .0001$; perceptual: $F(1,19) = 13.12$, $p < .005$). The perceptual task also showed a quadratic component ($F(1,19) = 38.39$, $p < .0001$). The quadratic component probably resulted from the levelling off (at 12 m) and decrease (at 15 m) in variable error. Cubic components were not present in either task ($p > .05$).

Perception and locomotion - correlations

As indicated above, differences between the perceptual and locomotor tasks depended on the type of error considered. Overall, constant and variable errors did not differ. Absolute error, on the other hand, showed performance that was less accurate on the perceptual task. Nevertheless, performance on the two tasks was related. Correlations between constant, absolute, and variable errors on the perceptual and locomotor tasks are shown in Table 4. Interestingly enough, all the significant correlations involved perception of the near target. Underestimation of the number of units to the 3 m target related to undershoots at all distances when subjects walked with their eyes closed. At the near target, absolute errors were significantly correlated while variable errors showed a trend be related on the two tasks. These data indicate that individuals who made accurate estimates of the distance to the near target also walked accurately. Mean errors collapsed over all target distances and errors at the 9 m target were not correlated on the two tasks.

Constant, absolute, and variable errors at the near target, on the perceptual task, were not only correlated with the corresponding errors on the locomotion task, but also related to other types of error

Table 4
Correlations between errors on a target-directed locomotion task and a target distance perceptual task

Locomotor errors	Perceptual errors		
	3 m	9 m	all
Constant			
3 m	.4636*	.3075	.2488
9 m	.4087#	.2679	.1565
all	.4550*	.3273	.2638
Absolute			
3 m	.4948*	.1384	-.0774
9 m	.3868#	.1660	.0805
all	.3520#	.1274	-.0213
Variable			
3 m	.4269#	-.2171	-.1284
9 m	.3040	-.0165	-.1091
all	.3423#	-.1620	-.1075

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$.
$n = 20$.

and other target distances (see Table 5). As can be seen in Table 5, in many instances, variable errors at the near target on the perceptual task correlated significantly with performance on the locomotion task. The relation was especially strong between variable error on the perceptual task and absolute errors on the locomotor task, where all the correlations were above .50. Table 5 also shows a number of trends and significant correlations between constant and absolute errors at the near target on the perceptual task and locomotor errors. Other correlations between perceptual and locomotor performance were not significant.

Spatial ability and locomotion

Performance on the locomotion task was not significantly correlated with scores on any of the tests of spatial ability (see Table 6). When the direction of the correlations was considered, ignoring the lack of significance, then a trend (Sign test: $p = .10$) for a negative relation between spatial scores and locomotor error was apparent. This trend indicated that as locomotor errors increased, spatial scores decreased. Nineteen of the 27 correlations were in the negative direction, suggesting a very weak relation between locomotor accuracy and spatial ability.

Spatial ability and perception

Scores on the spatial tests showed a number of significant correlations with performance on the perceptual task (see Table 7). Mean absolute errors were correlated with scores on Cube comparisons. Absolute errors also showed a number of trends to be related to spatial ability. In all cases, the trends indicated that larger perceptual

Table 5
Correlations between errors at the near target on the perceptual task and errors on the locomotion task.

Locomotor errors	Perceptual errors at 3 m		
	Constant	Absolute	Variable
Constant			
3 m	.4636*	.4341#	.4267#
9 m	.4087#	.2357	.5449*
all	.4550*	.2328	.4959*
Absolute			
3 m	.4057#	.4948*	.5675**
9 m	.3552#	.3868#	.5215*
all	.4502*	.3520#	.5442*
Variable			
3 m	.3318	.2169	.4269#
9 m	-.3321	-.1021	.3040
all	.4194#	-.0382	.3423#

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, **$p \leq .010$.
$n = 20$.

Table 6
Correlations between locomotor errors and scores on paper and pencil tests of spatial ability

	Test		
	Money Road Map	Paper Folding	Cube Comparisons
Error			
Constant			
3 m	.0215	-.0958	-.0843
9 m	-.0198	.1552	.2273
all	-.0177	.1617	.1494
Absolute			
3 m	-.0862	-.0364	.1369
9 m	-.3093	-.2700	-.1841
all	-.1376	-.1383	-.0143
Variable			
3 m	-.0600	.1797	.1929
9 m	-.2691	-.1419	-.2007
all	-.1859	-.2922	-.3545#

Note.
Two-tailed tests of significance: #$p \leq .10$.
$n = 20$.

Table 7
Correlations between errors on a target distance perceptual task and scores on paper and pencil tests of spatial ability

	Test		
	Money Road Map	Paper Folding	Cube Comparisons
Error			
Constant			
3 m	-.0541	-.2987	-.2762
9 m	-.0092	-.3106	-.2874
all	-.0820	-.3053	-.2749
Absolute			
3 m	-.3610#	-.1686	-.0615
9 m	-.3599#	-.4042#	-.3626#
all	-.2621	-.3131	-.4392*
Variable			
3 m	-.5634**	-.2891	-.1627
9 m	-.2097	-.0811	-.0485
all	-.1525	.2366	.2097

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, **$p \leq .010$.
$n = 20$.

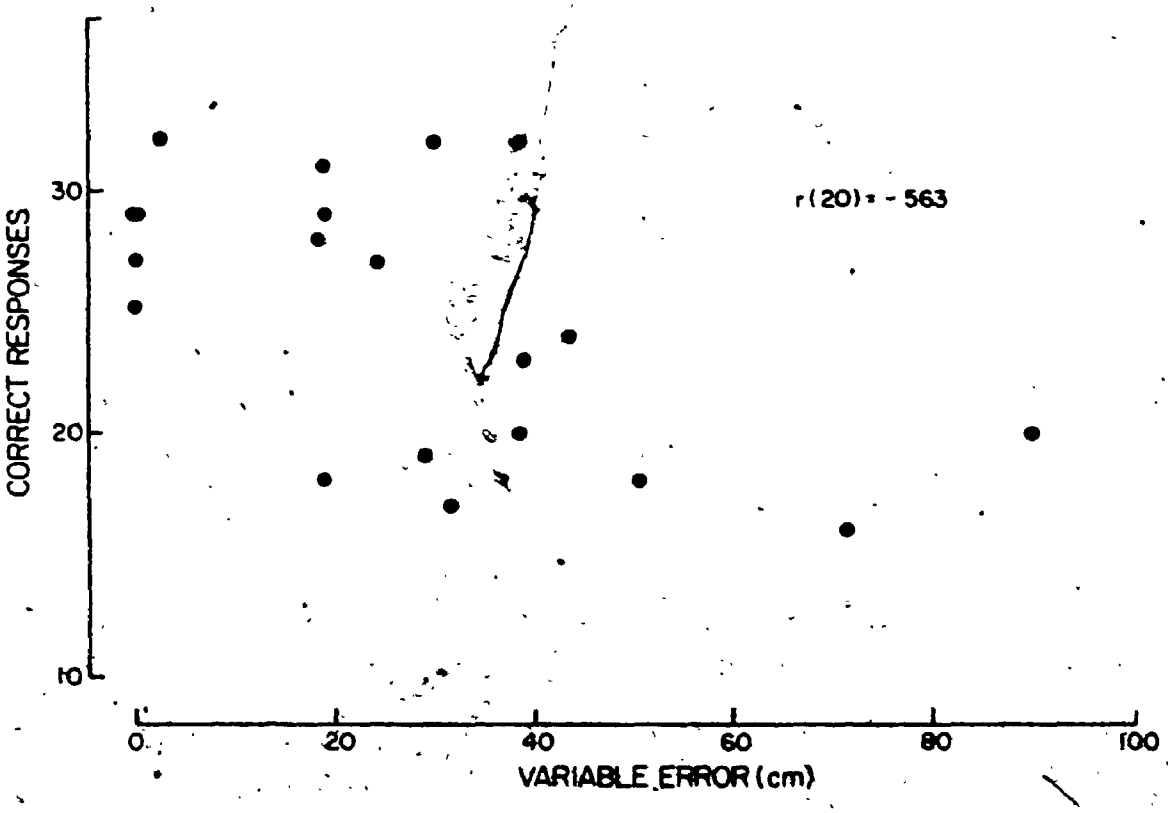
errors were associated with lower scores on the written tests. The strongest correlation, however, was between variable error for the 3 m target and performance on the Money road map test (see Table 7). Figure 19 shows that subjects who were consistent (low variable errors) in their choice of the number of units the 3 m target was away, had higher scores on the Money road map test.

If the direction of the correlations between perceptual task and the tests of spatial ability are considered, then the strength of the relation between these tasks becomes even more apparent. Twenty-five out of the 27 correlations were negative, indicating that increased perceptual errors were associated with lower spatial scores. This is a highly significant result (at the .01 level only 21/27 of the correlations need have been in the same direction).

Spatial ability, perception, and locomotion

It was puzzling that the relationship between perceptual errors and spatial ability appeared to be independent of the relationship between perceptual errors and locomotor errors. While variable errors at the 3 m target on the perceptual task were related to most locomotor errors and were related to performance on the Money road map test, there was no relation between locomotor errors and performance on the Money. Partial correlations controlling for the effect of the Money road map test were performed in an attempt to evaluate the contribution of spatial ability to the correlation between perceptual and locomotor errors. Controlling for the effect of the Money road map (see Appendix A, Table A-1) and for the effects of all three of the spatial tests (see Appendix A, Table A-2) did not produce substantial differences in

Figure 19. Scores on the Money road map test (number of correct responses) are plotted with respect to variable errors (cm) at the 3 m target on the perceptual task (n = 20).


r(20) = - 563
CORRECT RESPONSES
30
20
10
0
20
40
60
80
100
VARIABLE ERROR (cm)

the pattern of correlations found between performance at the near target on the perceptual task and locomotor errors at the selected target distances.

Discussion

A number of interesting relations were apparent in the data presented here. Differences and similarities between the performance perceptual and locomotor tasks depended on the type of error examined.

Perception of target distance

Performance on the target distance estimation task was much as would have been expected based on findings reported in the literature (Gibson & Bergman, 1954; Harway, 1963; Poulton, 1975). Increased target distance was associated with increased estimation errors. Reduced variability at the 12 and 15 m targets on the perceptual task might have resulted from additional contextual information available to the subjects when they estimated the distance to the target with their eyes open, but not when they walked with their eyes closed. It is also possible subjects remembered previous estimates of target distance for the final two target positions more easily than they remembered what they had said about intermediate positions. There was an indication of reduced variable error at the final target position in several of the experiments presented in previous chapters (chapter 1; Experiment 1 and chapter 2; Experiment 5) suggesting that subjects might recognize that they have seen the final target before and remember their previous response.

Perception and locomotion

Locomotor performance did not show a pattern of correlations with perceptual performance. However, competence in estimating the number of arbitrary units to the near target on the perceptual task correlated with competence on the locomotor task at all the target distances examined here. This relation between perceptual and locomotor performance was especially evident with constant and variable errors. Using the example of constant error, we see that subjects who underestimated the distance to the near target, on the perceptual task, also underestimated the distance to all targets when they walked with their eyes closed. Constant errors are thought to relate to perceptual processes (Laabs, 1979; Laabs & Simmons, 1981). The data presented here supports the suggestion that constant errors relate to perceptual processes. First, constant errors did not differ on the perceptual and locomotor tasks. Second, constant errors on the perceptual and locomotor tasks were correlated. Thus, it might be assumed that perceptual processes were the same when subjects estimated the distance to a target, but did not walk, as when they estimated the distance to the target and walked with their eyes closed.

Variable errors are thought to be enhanced by factors that increase memory load (Laabs, 1979; Laabs & Simmons, 1981). The fact that variable errors at the near target on the perceptual task correlated with errors on the locomotor task may suggest that the memory load was similar on both tasks. The lack of a difference between variable errors on the two tasks would also seem to support this position. The decrease in variable error at the 12 and 15 m

target distances on the perceptual task might indicate better coding of these distances.

On the other hand, absolute error on the perceptual task did not show the same pattern of correlations with locomotor performance. This finding and the fact that absolute errors were significantly larger on the perceptual task might suggest that absolute error was influenced by a factor specific to the perceptual task. A possible factor was the necessity to translate distance into arbitrary units. In both the locomotion and perceptual tasks presented here, target 'distance' was converted into a specific number of units. On the locomotion task, a majority of subjects estimated the number of paces to the target spontaneously (Experiment 2 of chapter 1). This process was analogous to that required in the perceptual task, except that on the locomotion task the unit was self-referenced rather than arbitrary. The greater accuracy on the locomotion task suggests that additional environmentally relevant information was available about pace length. Since errors on the perceptual task were so large, there was no way to evaluate Woodworth's (1899) claim that a substantial source of error comes from the translation of a perception into action (Woodworth, 1899).

A relation between perceptual and locomotor errors did not extend to all comparisons. Errors averaged over all target distances and errors at the 9 m target did not correlation between the two tasks suggesting that that there was something special about the 3 m target. It might be argued that performance on the perceptual task for the near target was not affected by difficulty in judging the relationship

between the unit measure and the target distance. Errors at other distances might have been enhanced by the requirement of translating target distance into arbitrary units. Therefore, errors in perception of the distance to a target need to be dissociated from errors that result from translating that perception into arbitrary units. It would be well worth examining the relation between perceptual and locomotor performance using a perceptual task that gives a more direct indication of the magnitude of errors associated with perception of the distance to a particular target.

Spatial ability relates to perceptual performance

There was only very limited evidence supporting a relation between spatial ability, as measured by the Money road map, Paper folding and Cube comparisons tests, and locomotor accuracy. However, a relation between perceptual accuracy and spatial ability was clearly demonstrated. Thus, the finding that throwing accuracy relates to spatial ability (Jardine & Martin, 1983; Kolakowski & Malina, 1974; Watson, 1985) can be extended to accuracy on target distance estimation, but not to target-directed locomotion. Subjects who were consistent (small variable errors) in their estimates of the number of units the near target was away also had the best scores on a test of direction sense. The data also suggested that smaller absolute errors on the perceptual task related to better scores on several written tests of spatial ability. The correlations between performance on the perceptual task and the written tests of spatial ability reported here were within the range that has been reported for correlations between spatial ability and visuomotor performance (r = -.18 to -.29, Jardine &

Martin, 1983; r = -.37, Kolakowski & Malina, 1974; and r = -.39 to -.79, Watson, 1985).

It is possible that if more subjects had been used in the present experiment, then the weak relation between locomotor performance and spatial ability may have reached significance. It is also possible that other written tests spatial ability like the Guilford-Zimmerman test (1953) would show a relation between spatial ability and locomotor performance. In Guildford-Zimmerman, as with the Money road map test, subjects must keep track of their own orientation relative to changes in the environment, not just keep track of changes in an external object (Cube comparisons and Paper folding). Tests that require just such a subjective point of view may be more likely to show a relation to locomotor performance than tests that do not. More research will be necessary to determine, if indeed, a weak relation exists between spatial ability and the ability to walk to a target in the immediate environment without visual feedback.

The ability to walk accurately to a target without visual feedback, therefore, does not seem to depend on either visualization or orientation spatial abilities. Locomotor accuracy does, however, appear to relate to an ability to translate the distance of a near target to arbitrary units. In turn, the ability to determine the number of arbitrary units it is to a near target relates to spatial ability. Apparently, factors controlling locomotor performance, at all target distances, are related to those required for good 'perceptual' performance at a near target, but are not the same as those required to perform the Money road map test.

Similarities, as well as differences, exist between the perceptual and locomotor tasks used here and the throwing tasks reported to correlate with spatial ability in the literature. All three tasks require perception of target distance. Locomotion and throwing, aimed at a distant target, not only require perception of target distance, but also require translation of those spatial coordinates into action. According to Woodworth (1899), substantial errors can occur in the conversion of a perceived distance into a motor output. For example, errors may be made in taking the 'correct' number of steps when walking without visual feedback or in exerting the 'correct' amount of force when throwing. The lack of correlation between locomotor performance and spatial ability seems to suggest that the ability to translate a perceived distance into locomotion does not depend on spatial ability.

In the locomotion task, subjects not only had to estimate the distance to the target, they also had to remember the location of the target as the walk progressed. Throwing and hammering do not have this memory component. The relation between spatial ability and visuospatial memory has not been established. Such a relation may vary independently, such that locomotor performance in open-loop conditions may relate to the ability to remember visuospatial information and not to spatial ability as measured by the standard written tests. It should be noted, however, that many of the written tests of spatial ability are thought to contain a short-term memory component (see McGee, 1979).

Summary

The suggestion that the ability to walk to a target in the immediate environment with eyes closed would relate to basic perceptual and cognitive processes received some support. The present findings suggest that the relation is complex. So, for example, even though spatial ability may contribute to the ability to convert near spatial locations into arbitrary units, other factors exert control over locomotor behavior directed to those spatial coordinates. Further investigation will be necessary to determine whether the effects of target distance perception are specific to the task used here or represent general relations that are independent of task.

CHAPTER 4

INDIVIDUAL DIFFERENCES IN TARGET-DIRECTED LOCOMOTION

Individual differences in spatial ability are well documented. Sex differences favoring males have been found reliably on both paper and pencil tests (for reviews see Harris, 1978, 1980; McGee, 1979; and Newcombe, 1982) and on visuomotor tasks (for example, ball throwing: Jardine & Martin, 1983; pointing: Sandström, 1951; and dart throwing and hammering: Watson, 1985). Sandström (1951) reported that females made larger errors than males on a number of visuomotor pointing and reaching tasks. In an experiment where subjects pointed to a luminous point in a darkened room, the errors of the females were about 30% greater than the errors of the males. Recently, Watson (1985) found females were significantly less accurate than males on a task involving dart throwing. He also showed females were less accurate hitting a target with a hammer. Average radial displacement errors were between about 30% (hammering in the dominant and non-dominant hands) and 60% (dart throwing in the non-dominant hand) larger in the females. Genetic, hormonal, and environmental influences have all been considered as possible factors contributing to the superior performance on tests spatial ability by males (see Harris, 1978, 1980; and McGee, 1979).

In the present series of experiments, individual differences in accuracy on the target-directed locomotion task were apparent -- females tended be less accurate than males when they walked with their eyes closed. The data presented in the following section were

collected in the course of Experiments 1-6 (chapters 1 and 2). The effect of sex on locomotor accuracy was not presented in the previous chapters because of the small number of subjects in each experiment. Information about a number of potentially relevant individual variables was collected in an attempt to determine if the sex difference could be attributed to variables such as pace size, height, and sports activity. First, errors might simply have been related to the number of steps the subject took. Females, who are generally smaller than males, may have been taking smaller steps and, therefore, more steps. Second, taller subjects, the males, may have been better able to take advantage of the 'angle of regard' as a cue to target distance. Recently, experimental evidence indicates that the angle of regard can be used as a distance cue (Wallach & O'Leary, 1982). The angle of regard is the angle between the ground and a line extending from the eyes of an observer to an object of regard. "The sine of this slope angle is inversely proportional to the distance between the eyes and the object, and the same is approximatley true of the slope angle itself" (Wallach & O'Leary, 1982, p. 145). As a target gets further away, the change in the angle of regard becomes smaller and, therefore, it provides less accurate information about the distance to a target. It could be argued that taller subjects might be able to use cues about target distance provided by the angle of regard over a wider range of distances than shorter subjects. It should be noted, however, if height provided an advantage in the use of distance information available from the angle of regard, differences in locomotor accuracy would be more apparent at the far targets. Third, males tend to engage

in more sports activities than females, as a consequence, may have more experience relating visuomotor output to the external environment.

The relation between performance accuracy and a number of other variables was also examined. It is possible that differences in ability to determine the location of the target existed between subjects who needed visual correction and those who did not. Therefore, information about visual correction was also collected and analyzed. Perhaps visual corrections were not adequate and those subjects who wore contact lenses or glasses would perform more poorly than those who did not need correction. It was also possible that subjects who were uncertain of the target position walked more slowly than those who thought they knew where the target was. Conversely, subjects who walked more slowly might have been more careful in executing the task, thereby committing smaller errors. To this end, the relation between walking speed and locomotor accuracy was also examined.

Divisions of space

A number of investigators have suggested that the space surrounding us is not uniform (Grüsser, 1982a, 1982b; Thomson, 1980, 1983), although just how space is differentiated has not been thoroughly investigated. Thomson (1980, 1983) suggests that locomotor behavior toward targets that are less than 6 m away is preprogrammed and not controlled by visuospatial memory. However, if the target is beyond 6 m, he suggests that short-term memory controls locomotor behavior. Evidence for a short-term memory of target locations, presented in an earlier chapter, did not support a distinction between

near and far targets. A 30 s delay resulted in an equivalent deterioration in performance at all targets. Conversely, an advantage for near targets, those 3 m away, was suggested by data indicating that accuracy without visual feedback did not differ from accuracy with full visual feedback. If different processes or abilities control locomotion toward near and far targets, then one would predict a weak relation between performance at these different distances. In contrast, if performance is governed by a common mechanism, significant correlations would be predicted across target distances.

The subjects were the 38 right-handed females and 40 right-handed males who participated in the target-directed locomotion experiments discussed in the previous chapters. The mean age was 21.85 (s.d. = 3.42) years. Complete data were not obtained in Experiment 5 of chapter 2 and Experiment 1 of chapter 1. In all other experiments, subject information was routinely collected.

Prior to beginning the locomotion experiment, sex, age, if the subject wore glasses or contact lenses, height, and number of sports played on a regular basis were recorded. Since all subjects who reported needing visual correction wore their glasses or contact lenses during the locomotion task, vision was recorded as normal or corrected. Height was either measured or simply reported by the subject. The number of different sports served as an approximate measure of physical activity and/or physical experience levels. In addition to the above measures, pace length, and walking speed were calculated from the locomotor data. The number of steps the subject took were counted on five trials sampled at random from walks at various distances. Pace

length was calculated by dividing the number of steps taken (to the nearest quarter step) by the distance walked. Walking speed, which was calculated on all trials, was obtained by dividing the distance walked by the time taken. Both the speed and pace measures represent mean data and do not reflect variations during any one trial. In other words, mean walking speed data do not reflect speed changes within a trial. Nor do mean pace measures indicate whether subjects adjusted their stride length as they approached the target.

Data analysis

Subject variables were correlated with performance on the locomotion task. Mean constant, absolute, and variable errors collapsed over all distances, and mean errors at the 3 m and the 9 m targets were selected for Pearson product-moment correlations. These distances were selected so that effects due to target distance could be examined. The 9 m target was chosen because it was common to all the experiments and because the relationship between target distance and variable error was linear up to this distance in all experiments. Since the magnitude of errors differed between experiments, error data from each experiment were subjected to z-score transformations prior to the correlational analysis. Z-scores of the performance measures, including walking speed, were then examined in relation to the untransformed subject variables; sex, visual correction, pace length, height, and number of sports. The correlations between z-scores of locomotor errors at the selected target distances were also examined. In addition, variables that correlated significantly with sex were each examined with a one-way analysis of variance.

Results

Correlations between subject variables

As was expected, sex correlated with height, pace, and number of sports, but not with visual correction (see Appendix B: Table B-1). The males were taller ($F(1,69) = 49.56$, $p < .0001$), had longer pace lengths ($F(1,68) = 6.86$, $p < .05$), and engaged in more sports ($F(1,56) = 13.78$, $p < .01$), but an equal number of males and females had corrected vision. Subjects with corrected vision took smaller steps and were shorter than subjects with normal vision. Taller subjects took longer strides and participated in more sports activities. Finally, subjects who took longer strides tended to participate in fewer sports.

Correlations between subject variables and locomotor performance

All subjects. As shown in Table 8, a number of significant correlations existed between locomotor errors and subject variables. Sex and height showed significant correlations with absolute errors. Females and shorter subjects made larger overall absolute errors and larger absolute errors at the far target. There was also a trend for absolute errors at the 3 m target to be greater in females. Mean constant errors collapsed over all distances were correlated with sex, indicating that females tended to undershoot the target more than males. Subjects who had corrected vision tended to have larger absolute errors. As participation in sports activities increased, there was a tendency for absolute errors to decrease. Both the normal vision and sports activity advantages were not present at the near target. Pace length was not significantly related to accuracy on the

Table 8
Correlations between z-scores of locomotor errors and subject variables

	Measure				
	Sex[a]	Vision[b]	Pace[c]	Sports[b]	Height[d]
Error					
Constant					
Mean	.2014#	.0113	.0946	.1571	.0411
3 m	-.1089	-.0258	-.0694	.0306	-.2929*
9 m	.0782	-.0896	.1689	.0722	.0072
Variable					
Mean	-.0789	.0477	-.0202	.0268	-.0243
3 m	-.0650	-.0946	-.0114	-.1105	-.1203
9 m	.0429	.0520	.0838	-.0850	-.0525
Absolute					
Mean	-.3921***	.2033#	-.1431	.1971#	-.3675***
3 m	-.1814#	.1208	-.0958	-.0708	-.0794
9 m	-.2285*	.1925	-.1483	-.2042#	-.2523*

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, **$p \leq .005$.
a $n = 78$.
b $n = 58$.
c $n = 70$.
d $n = 71$.

target-directed locomotion task.

Since the trend for absolute error to be related to height and sports activity could be a reflection of the effect of sex on absolute error, the subject variables were examined separately by sex. The pattern of correlations differs in females (Appendix B: Table B-2) and males (Appendix B: Table B-3). However, neither males nor females showed a relation between the number of sports activties and locomotor error.

Females. In females, visual correction and pace length did not correlate with any of the error measures. Height showed a strong correlation with absolute error. As is shown in Figure 20, taller females made smaller overall absolute errors. The advantage of taller females was also significant for the 9 m target and showed a trend at the 3 m target. Correlations between height and absolute error were in the opposite directions for males and females. Therefore, the overall relation between height and absolute error shown in Table 8 was due to the females.

Males. In the males, absolute errors at the near target increased with height. Taller males also undershot the near target (see Figure 21). In males, vision tended to be correlated with variable errors at the near target and constant errors at the far target: males with corrected vision tended to be less variable at the 3 m target, but undershoot the 9 m target more. Males with long strides had smaller absolute errors at the far target, but tended to overshoot it.

Figure 20. Z-scores of overall absolute errors plotted with respect to height in the females (n = 33) are shown.

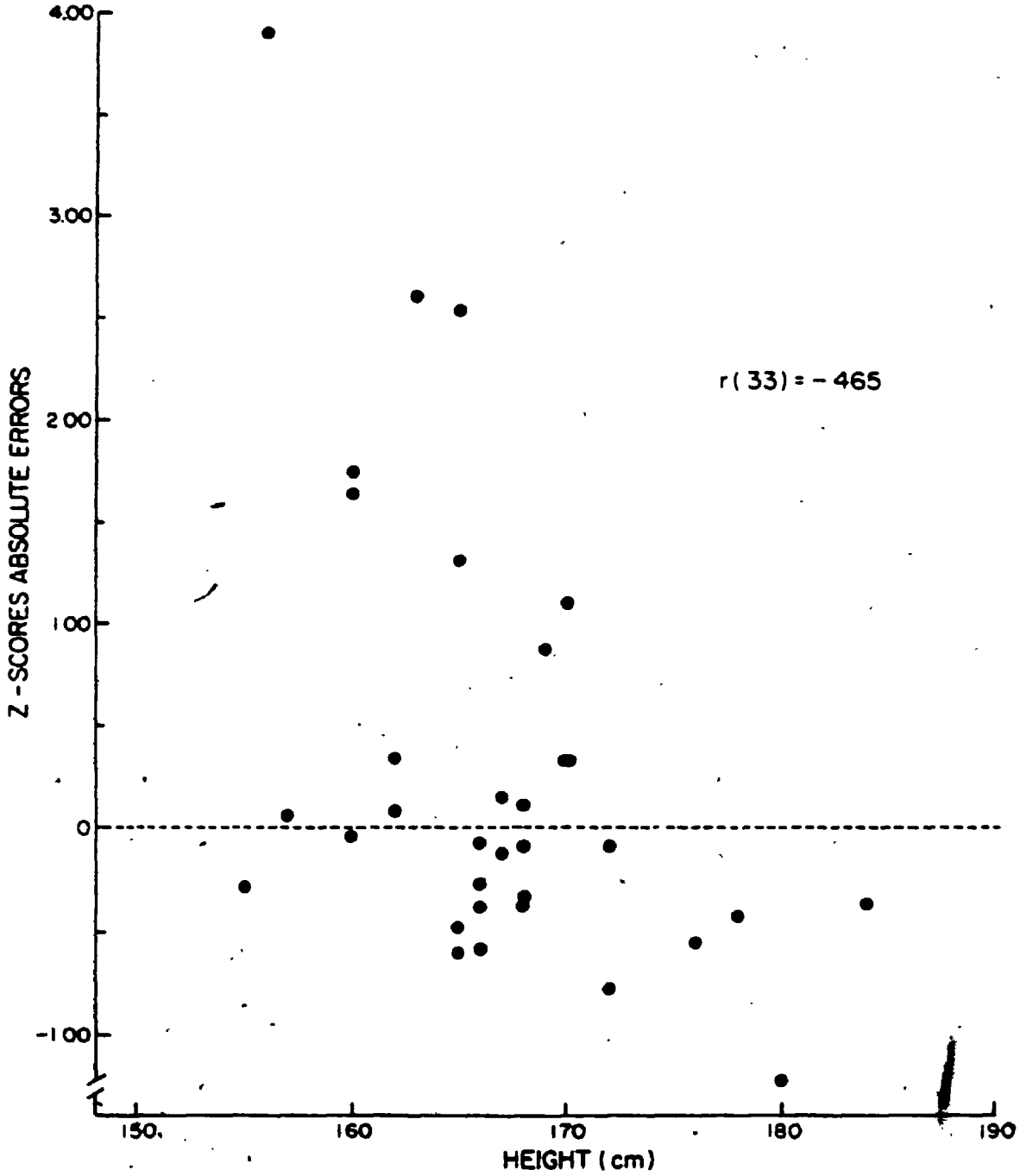
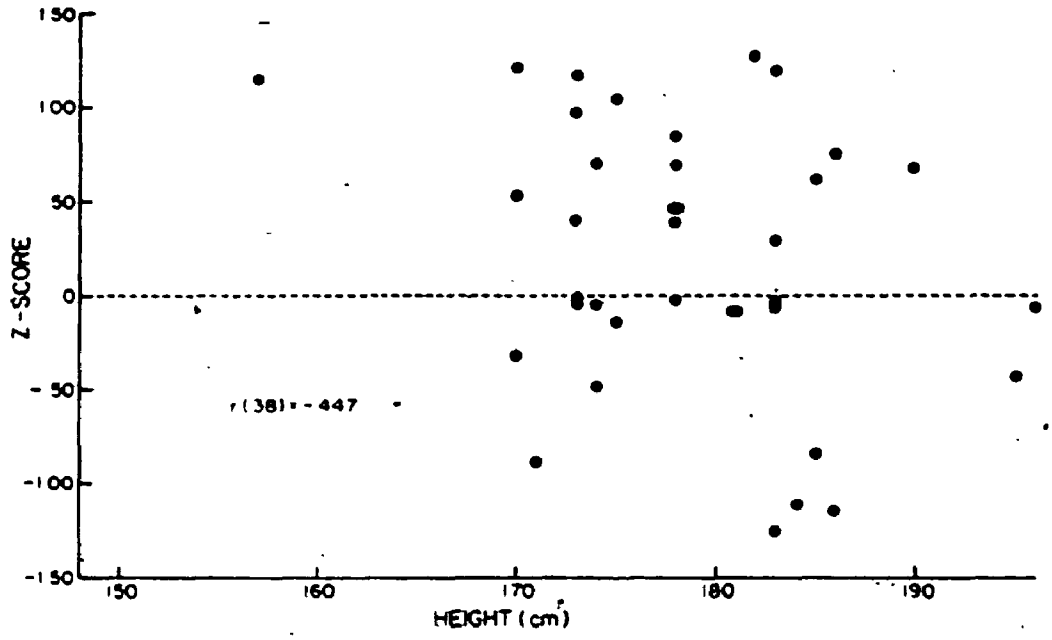

4.00
3.00
2.00
1.00
0
-1.00
Z-SCORES ABSOLUTE ERRORS
r(33) = -.465
150
160
170
180
190
HEIGHT (cm)

Figure 21. Constant error z-scores at the 3 m target plotted with respect to height in males (n = 38) are shown.


150
100
50
0
-50
-100
-150
Z-SCORE
r(38) = -447
150
160
170
180
190
HEIGHT (cm)

Walking speed and subject variables

There are a number of interesting correlations between walking speed and the subject variables (see Appendix B: Table B-4). Males and females walked at the same speed, but subjects with corrected vision walked more slowly than those without. Subjects who took longer strides walked more quickly than those who took smaller steps, but tall subjects did not walk more quickly than short ones. Subjects who participated in more sports walked more slowly than those who were less active in sports.

Although males and females walked at the same speed (see Table 8), and subjects of both sexes who had corrected vision tended to walk more slowly, the relationship between walking speed and other variables was not consistent in males and females (see Appendix B: Table B-5). Walking speed did not correlate with pace length and sports activities in females. In males, as pace length increased so did walking speed, but the number of sports activities decreased with increased walking speed. Height showed no relation to speed in either sex.

Walking speed and locomotor performance

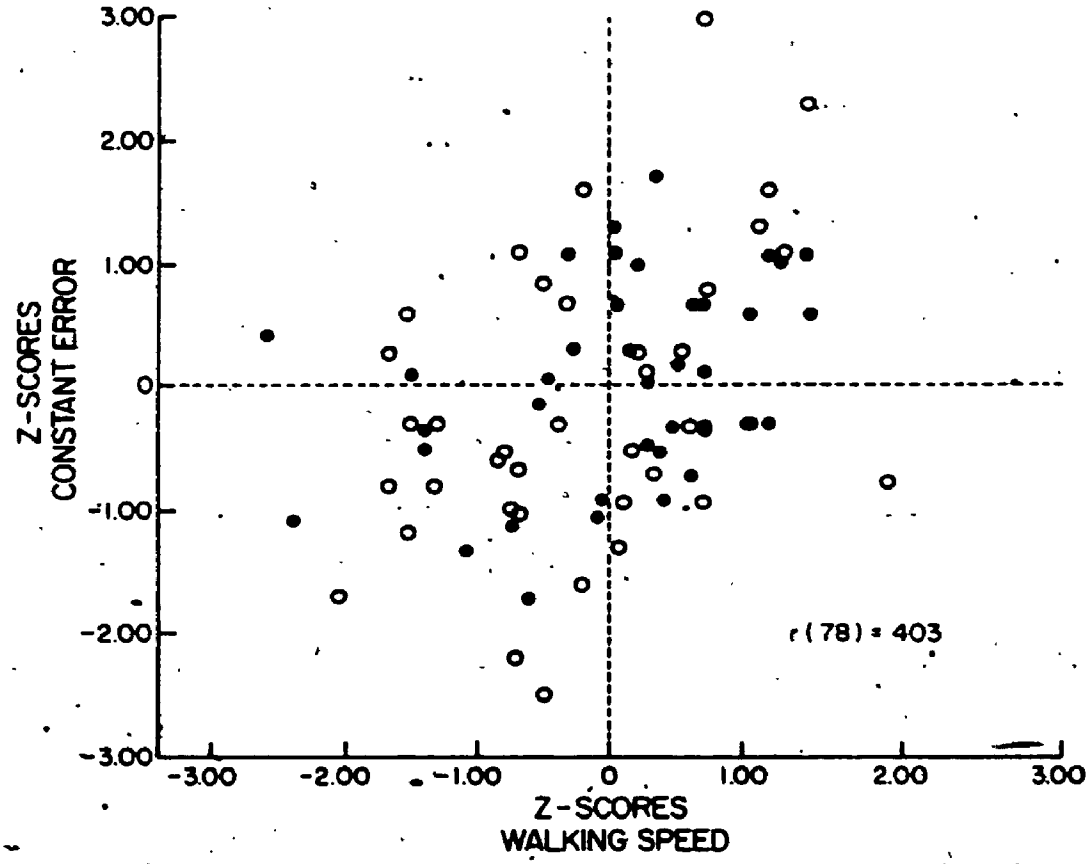
Walking speed correlated with constant errors, such that subjects who walked more slowly did not walk as far as subjects who walked more quickly (see Table 9). Although speed and constant errors were correlated across all the distances examined, the strongest relations were within a distance. Thus at the near target, walking speed and constant errors were highly significantly correlated, just as they were at the far target. Figure 22 shows the increase in constant error with walking speed at the 9 m target. Walking speed also showed some

Table 9
Correlations between walking speed and locomotor errors

	Walking speed		
	Mean	3 m	9 m
Error			
Constant			
Mean	.2187*	.2404*	.3457***
3 m	.1761#	.3081**	.2482*
9 m	.2304*	.2258*	.4032***
Variable			
Mean	.0321	-.0518	-.0607
3 m	.1465	.1194	.1492
9 m	-.0960	-.1381	-.1576
Absolute			
Mean	-.1415	-.2422*	-.2088#
3 m	.0725	-.0260	.0630
9 m	-.0947	-.1996#	-.1932#

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, **$p \leq .010$, ***$p \leq .005$.
$n = 78$.

Figure 22. Z-scores of mean constant errors are plotted with respect to walking speed for the 9 m target for both males (closed circles; n= 40) and females (open circles; n = 38).


3.00
2.00
1.00
0
-1.00
-2.00
-3.00
Z-SCORES
CONSTANT ERROR
r(78) = 403
-3.00
-2.00
-1.00
0
1.00
2.00
3.00
Z-SCORES
WALKING SPEED

relation to absolute error, but very little correlation with variable error.

As was shown in Figure 22, in both males and females, constant errors at the 9 m target correlated with walking speed indicating that the subjects who walked slowly undershot the target more than those who walked more quickly. But the relation between constant error and walking speed was more prevalent in females (see Appendix B: Tables B-6 and B-7). A number of significant correlations and trends between variable error in females (see Table B-6) and absolute error in males (see Table B-7) indicated that poorer performance occurred in subjects who walked more slowly than the average.

Relationship between errors at different target distances

As Table 10 shows, the different types of locomotor error were correlated between the selected target distances. Generally then, the same subjects were accurate across these target distances. Correlations between errors at the 3 m and 9 m targets give an indication of processes and/or response biases that may act on all targets versus those that may vary independently of target distance. Constant errors were correlated at the 3 m and 9 m distances. In other words, the same subjects were undershooting the target (see Figure 23) at both distances. Subjects who made large absolute errors at the near target were also making large absolute errors at the far target. However, the relation between variable errors at the two target distances was much weaker -- there was only a trend for a correlation.

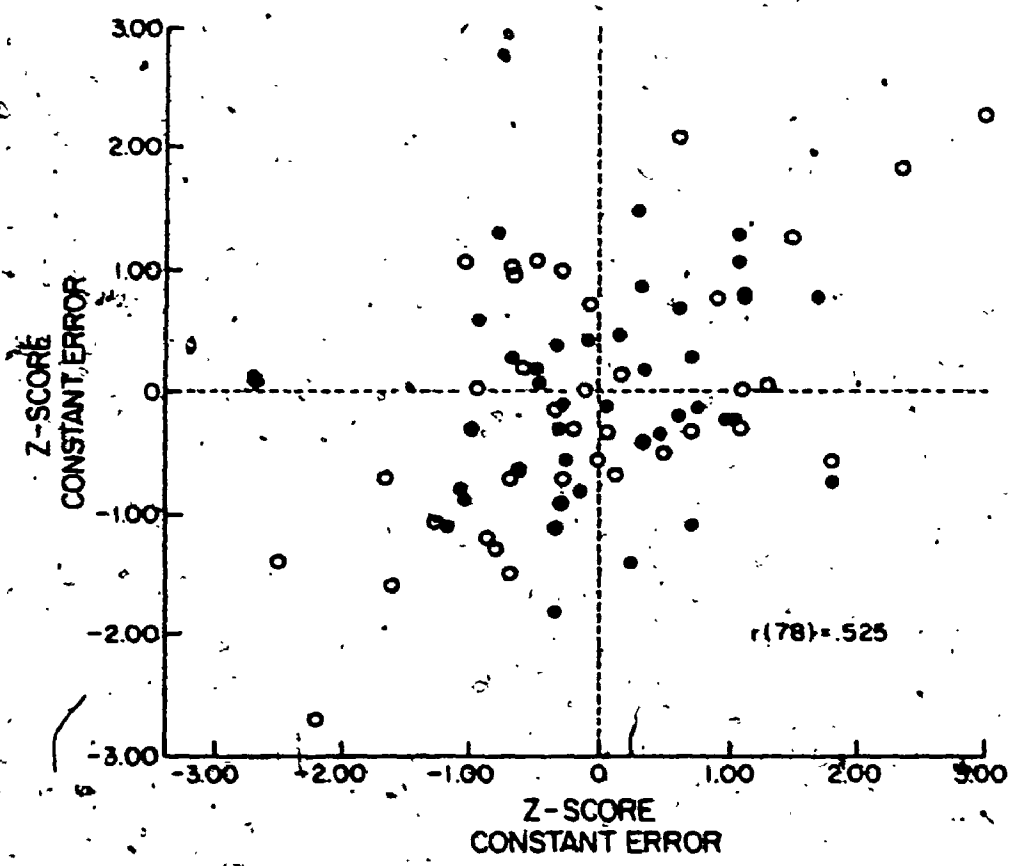
Correlations between errors at the 3 m target and overall mean errors were similar to those found between the 3 m and 9 m targets.

Table 10
Correlations between locomotor errors at selected target distances

	Interdistance error correlations		
Error	Mean x 3 m	Mean x 9 m	3 m x 9 m
Constant	.6216***	.8333***	.5253***
Variable	.2459*	.6353***	.2154#
Absolute	.5351***	.8082***	.4355***

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, ***$p \leq .005$.
$n = 78$.

Figure 23. Z-scores of mean constant errors at the 3 m target and the 9 m target are shown for both males (closed circles; n = 40) and females (open circles; n = 38).


3.00
2.00
1.00
0
-1.00
-2.00
-3.00
Z-SCORE
CONSTANT ERROR
r(78)=.525
-3.00
-2.00
-1.00
0
1.00
2.00
3.00
Z-SCORE
CONSTANT ERROR

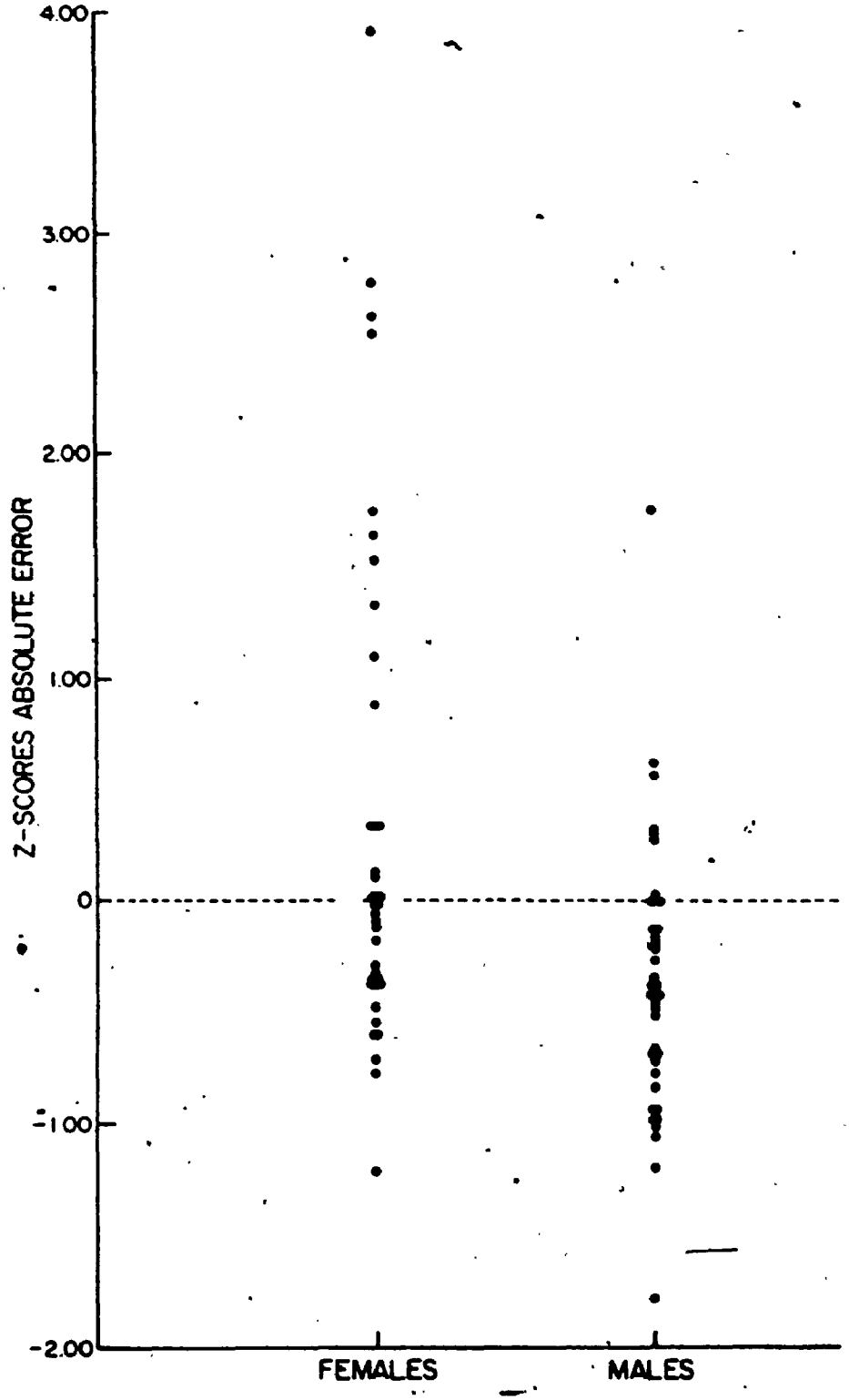
Correlations between overall performance and performance at the 9 m target were of limited interest. All types of error increased with target distance; therefore, errors at the far target would have contributed more to the mean error collapsed over all the target distances than errors at the near target would have. This notion was supported by the fact that although performance at the near and far targets each related to overall performance, the strongest relation was between overall errors and those at the far target.

When the sexes are considered separately, the relation between locomotor errors at the selected target distances remains the same for constant error (see Appendix B: Table B-8). As shown Figure 23, subjects of both sexes consistently undershot or consistently overshot both near and far targets. A significant correlation between absolute error at the 3 m and 9 m targets, however, was only apparent in the females. A significant relation between variable errors at the different target distances was not found in males. In females, there was a trend for near and far variable errors to be related.

Sex differences in locomotor performance

Absolute error. As stated above, females made larger asbolute errors ($F(1,76) = 13.81$, $p < .0001$) on the locomotion task (see Table 8). In Figure 24, z-scores of absolute errors collapsed over all distances are shown for both sexes. It is immediately apparent that the sex difference was due to a proportion of the females who performed poorly. Twenty-five percent of the females scored more than 1 s.d. above the mean, while only 3% of the males did. Of the females who performed poorly on the task, half scored more than 2 s.d. above the

Figure 24. Z-scores of mean absolute errors are shown separately for males (n= 40) and females (n= 38). Multiple overlapping points indicate that more than one subject had the same z-score.


4.00
3.00
2.00
1.00
0
-1.00
-2.00
Z-SCORES ABSOLUTE ERROR
FEMALES
MALES

mean. None of the males were as inaccurate. Three percent of the females showed superior locomotor performance (z-score $\geq$ -1.00) compared to 10% of the males. It is also worth noting that a majority of females scored within the range of the males. Even in this group of females, however, the scores of the males tended to be shifted toward better performance. For example, of subjects who scored between +1.0 and -1.0 z-scores, 10% of females scored -.6 or better while 28% of males scored below this level.

Less accurate performance by the females was evident in each experiment (see Appendix B: Table B-9). Although not all the individual experiments showed significant sex differences (see Appendix B: Table B-10), in every experiment mean absolute errors of the females fell above those of the males at all target distances with the exception of the 1 m and 3 m targets in Experiment 5. The lesser effect of sex at the near target was borne out by the finding that in 4 of the experiments, sex and distance interacted. In Figure 25, an example of the interaction between target distance and sex is shown.

Constant error. Constant errors collapsed over all distances tended to correlate with sex (Table 8). While on the whole, females tended to undershoot the target more than males ($F(1,76) = 3.21$, $p = .08$), a more detailed examination of the data showed, once again, that the effects were due to about 25% of the females whose scores were below a z-score of -1.0 (Figure 26). These females undershot the target more than average. In fact, the effect was less marked than it would have been if 2 females had not made very large overshoots. The tendency for females to undershoot the target more than males was

Figure 25. Mean absolute errors (cm) from Experiment 1 (chapter 1) are shown for females (n = 10, closed circles) and males (n = 10, closed triangles).

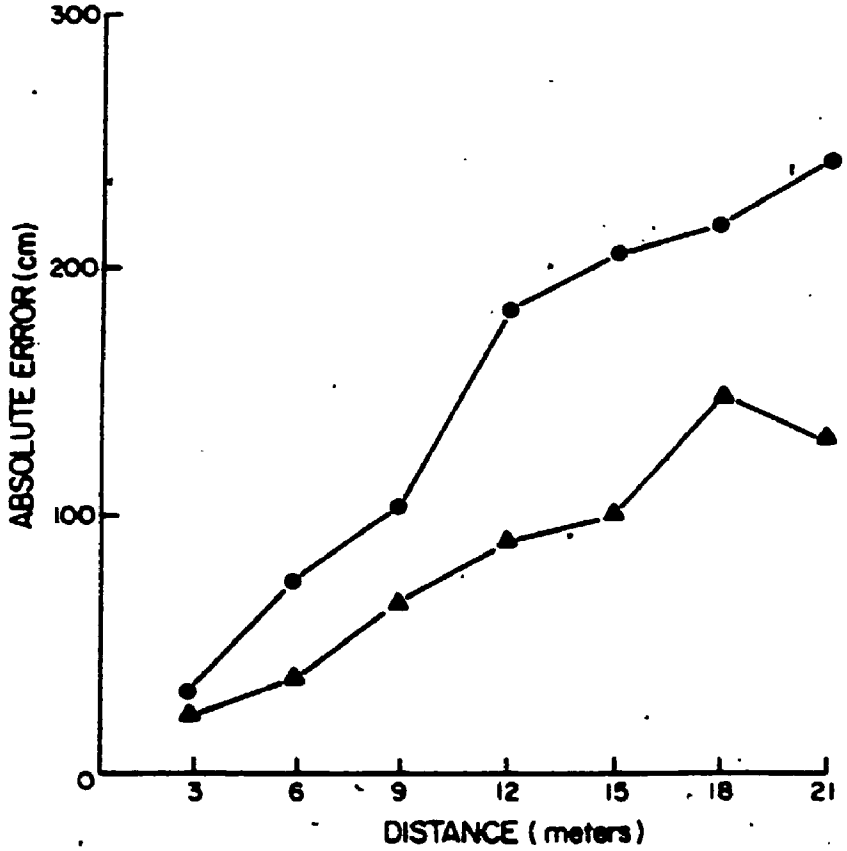
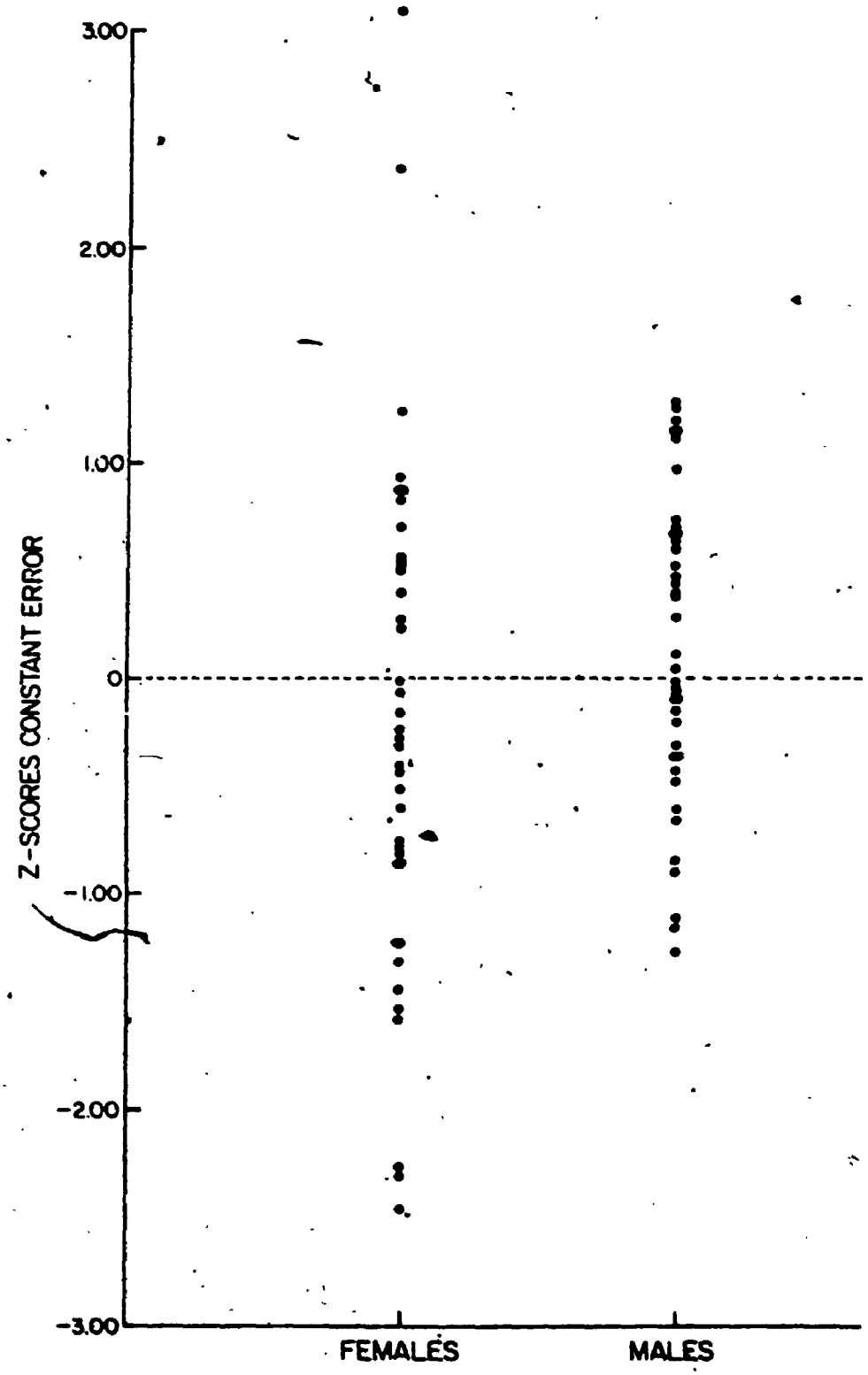

300
200
100
0
ABSOLUTE ERROR (cm)
3
6
9
12
15
18
21
DISTANCE (meters)

Figure 26. Z-scores of constant errors are shown separately for males (n = 40) and females (n = 38). Multiple overlapping points indicate that more than one subject had the same z-score.


3.00
2.00
1.00
0
-1.00
-2.00
-3.00
Z-SCORES CONSTANT ERROR
FEMALES
MALES

present in the individual experiments as a significant effect of sex and/or an interaction between sex and distance on constant errors (see Figure 27). The relation between constant error and sex was not as predominant as the relation between absolute error and sex (see Appendix B: Tables B-11 & B-12).

Variable error. Variable error did not show a relation between sex and performance. This was borne out by both the correlational analysis (see Table 8), the one-way analysis of variance ($F(1,76) = .476$, $p > .05$), and the results of the individual experiments.

Discussion

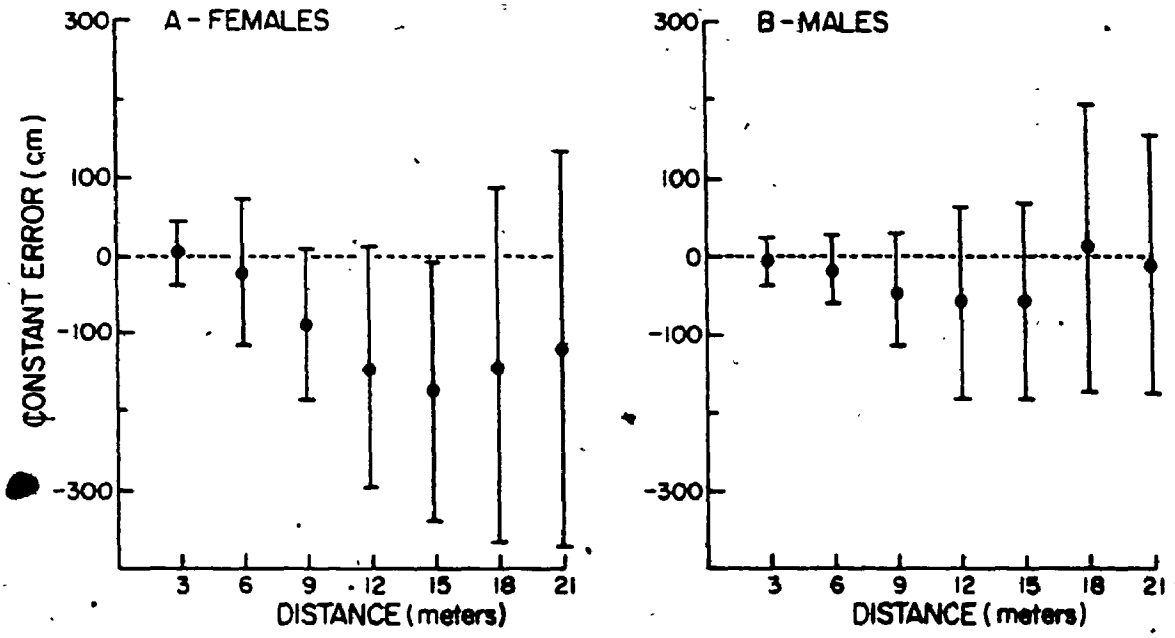
The data presented in this chapter give an indication of variables that affect accurate performance on a target-directed locomotion task. The relation between locomotor performance and other variables was not straightforward. Correlations often depended on the type of error and target distance examined. The sex of a subject, however, was an important variable affecting performance.

Target distance -- relations between near- and far-space

Distance to the target was one variable manipulated in the present experiments. Data presented in the previous chapters demonstrated that increased target distance resulted in decreased accuracy as measured by constant, variable, and absolute error.

The present analysis suggests that constant errors, which were highly correlated ($p<.001$) at the near and far targets, were affected by a process that acts over all distances. If constant errors reflect

Figure 27. Mean constant errors (cm) from Experiment 1 are shown for females (a; n = 10) and males (b; n = 10) as an illustration of the enhanced tendency for females to underestimate target distance.


A - FEMALES
B - MALES
CONSTANT ERROR (cm)
300
100
0
-100
-300
3
6
9
12
15
18
21
DISTANCE (meters)

perceptual processes as Laabs and his colleagues contend (Laabs, 1979; Laabs & Simmons, 1981) then target distance affected the perceptual processes of both males and females in the same way. In both sexes, subjects who undershot the 3 m target also undershot the 9 m target. Larger constant errors obtained in the females suggest that they were more prone to the influence of the same perceptual biases that affected all subjects. Conversely, one might argue that males were better able to compensate for perceptual biases.

Variable error seems to be affected by different factors than constant error as others have suggested (Laabs, 1979; Laabs & Simmons, 1981). First, performance at the near and far targets was not significantly related in either sex. Second, unlike constant and absolute error, variable errors did not differ between the males and the females. The dissociation between variable errors at these two distances may offer some support for a differentiation between the factors that control performance in near- and far-space (Grusser, 1982a, 1982b; Thomson, 1980, 1983). It is also possible that the memory load (Laabs, 1979; Laabs & Simmons, 1981) differed between the two target distance and it was this difference that resulted in the weak relation between variable errors at 3 and 9 m. If differences in memory load resulted in the low correlation between variable errors at the 3 and 9 m targets, then the data also suggest that males and females were able to remember the location of the target equally well.

Individual differences

In the series of experiments presented here, females on the average performed more poorly than males. This finding was in keeping

with the sex differences reported in the literature on tasks of spatial ability (Harris, 1978, 1980; McGee, 1979) and visuomotor ability (Jardine & Martin, 1983; Sanistom, 1951; Watson, 1985). Some investigators have also demonstrated a relation between spatial ability and visuomotor ability (Jardine & Martin, 1983; Kolakowski & Malina, 1974; Watson, 1985) while others have not (see chapter 3 of this volume). Why females performed more poorly than males on the locomotor task is not known. Variables such as height, pace length, and participation in sports activities, on which a random sample of males and females can be assumed to differ (and, in fact, do), did not account for the more inaccurate performance of the females.

Sex differences were not found with all types of locomotor error. Sex differences depended on the type of error and the target distance examined. Not all females performed more poorly than the males. A more detailed examination of the nature of sex differences in other visuomotor behaviors and spatial abilities may reveal a similar pattern of ability and disability in females. There is some suggestion that females not only commit larger errors on visuomotor tasks, but as a group are also less homogeneous than males (see the standard deviations of hammering and dart throwing performance in Watson, 1985).

One might suppose that males and females used different cognitive strategies to solve the locomotor problem used here and that those strategies resulted in the performance differences (Campione, Brown, & Bryant, 1985). Use of a verbalization strategy did not differ between males and females in Experiment 2 of chapter 1. Although overt cognitive strategies apparently did not differ between the sexes, other

strategy differences may have existed. Evidence supporting this notion comes from the finding that different variables affected the locomotor performance of males and females. For example, a relation between height and absolute errors was found only in the females. Taller females had smaller absolute errors. Females may have used the angle of regard as a cue to distance perception (Wallach & O'Leary, 1982) while males did not.

Walking speed and over- and underestimations of target distance

The relation between walking speed and constant error might suggest that a time-based phenomenon may be controlling performance. It must be stated at the outset that this notion is highly speculative and needs further investigation. The data presented here seem to indicate that subjects had an idea about how long they should walk. Subjects probably made this judgment at the start-line before they closed their eyes and started to walk. Apparently, variations in speed could not be corrected when vision was absent. If subjects walked too quickly they overshot the target, but if they walked too slowly they undershot it. Once again, females showed this phenomenon in an enhanced fashion.

Future research is necessary to determine if manipulating walking speed in the same subject would induce a shift in constant errors from underestimation to overestimation.

Summary

The locomotor performances of males and females differed. First, the females tended to underestimate the distance to the targets to a greater extent than the males. Second, females made larger absolute

errors than males, but did not make larger variable errors. Third, females who performed poorly did so at both near and far targets. Sex differences were also apparent in the correlations between performance on the locomotor task and other variables, such as, height and walking speed.

GENERAL DISCUSSION

Short-term memory for spatial location

In the first chapter, a failure to replicate Thomson's (1980, 1983) finding of a highly accurate short-term memory for target locations was reported. The biggest difference between the present data and those reported by Thomson was that, in the present experiments, walks without visual feedback were not as accurate as walks with visual feedback if the target was more than 3 m away. This was the case even when walks with partial visual feedback (subjects walking with their eyes open to a brief target) were compared to walks with full visual feedback. Thus, it appeared that information required to walk accurately to a nearby target was unavailable as soon as the subjects closed their eyes. Thomson (1985, 1986) has suggested that walking speed and pretraining with visual feedback are critical variables in obtaining evidence of a highly accurate short-term memory. In the experiments reported here, increasing walking speed and pretraining did not result in the high degree of locomotor accuracy necessary to demonstrate Thomson's short-term memory effect.

In retrospect, it seems counterintuitive to propose a short-term memory that would decay so abruptly as to make performance range from very accurate to inaccurate within the span of 1 s (the difference between 8 and 9 s walks). In many real-life situations, a sudden loss of accuracy could mean the difference between colliding with an obstacle or stopping in time. An unstable memory of this sort is not only unlikely, but stands in complete contrast to the much more stable

(if less accurate) short-term memory demonstrated here. In an experiment reported here, a 30 s delay resulted in slightly decreased accuracy over and above the substantial deterioration in performance that could be attributed to the fact that the subjects did not have visual feedback.

Continuous or discontinuous visual feedback?

A theoretical problem with the position taken by Thomson (1980,1983) is the assumption that a highly accurate short-term memory is necessary to the argument that visual feedback is obtained in a discontinuous manner. I will argue that rather than being evidence for discontinuous visual feedback, such an accurate short-term memory is neither evidence for nor against this kind of feedback. Indeed, a strict interpretation of Thomson's conception of the problem could lead one to the conclusion that an accurate short-term memory is evidence for continuous feedback. Thomson has simply moved the problem of dividing attention between parts of the environment from the 'sensorium' to 'memory'. Thomson (1980, 1983) suggests that a highly accurate representation of the target location acts as a substitute for actual visual feedback. Thomson (1983) commented that subjects in his experiments reported being able to see themselves walking toward the target and that subjects were very possibly "....internalizing a map or image of the environment and were using this instead of either direct vision or a 'blind' motor program to guide themselves" (p. 249, emphasis mine). The 'image' cannot be degraded or distorted, since performance controlled by the image is equivalent to performance controlled by the 'real thing'. Therefore, the rate of sampling for

real and imaginary targets must be the same. Thus, by posing the problem as one of continuous or discontinous feedback, Thomson seems to have demonstrated that locomotion controlled by an accurate short-term memory requires continuous rather than discontinuous feedback. However, it may be misleading to infer, as Thomson appears to, that if visual feedback is used to control locomotion then it is obtained in a continuous manner. No one has examined how often subjects sample targets during visually guided locomotion. Some indirect evidence suggests that sampling may be discontinuous (Lee, 1977; Lee & Thomson, 1982).

Elliott (1986) concluded that a failure to replicate Thomson was evidence that one needed continuous visual feedback during locomotion. In contrast, I contend that for locomotion in a relatively uncluttered environment intermittant visual feedback should be sufficient. Performance with eyes closed deteriorated remarkably little during a 30 s wait followed by a 12 s walk. This would suggest that one can walk to within about a pace or two of a target that is 12 m away, even when a wait of 30 s precedes the walk. At a pace or two from the target, information provided by sampling the target again would lead to locomotor accuracy equivalent to that provided by full visual feedback.

Moreover, I would argue that locomotor accuracy is necessary only as a target is reached. This concept is supported by evidence suggesting that up-dated visual information is most likely to be obtained at or near an intended target. It seems paradoxical that most other demonstrations of discontinuous visual feedback (aside from

Thomson's) suggest that there are two stages to a movement, an initial inaccurate stage followed by a corrective stage. For example, visually guided reaches are considered to contain an inaccurate ballistic phase followed by a visually controlled corrective phase (see Fisk & Goodale, 1985; Goodale, Pelisson, & Prablanc, 1981). The corrective phase occurs very near the intended target. Further evidence that corrective movements occur near a target comes from Lee and Thomson (1982) who found that skilled long-jumpers visually adjusted their pace length on the last few strides before they jumped. Although the pattern of locomotor errors found in the present investigations seems to indicate that a similar two-stage model of target-directed locomotion is probable, direct experimental evidence of such target sampling is necessary.

At the present time, my colleagues and I are examining the nature of target sampling during target-directed locomotion. Subjects wearing a pair of shuttered goggles walked to targets at 2, 6, 10, and 14 m. Following a 4 s exposure to the target, the shutters closed and subjects walked toward the target. Subjects stopped walking when they felt they wanted another look at the target. Subjects were free to sample the target as often as they liked. Our preliminary findings indicate that subjects walk most of the way to a target before they take a second look at it. In most cases, about 80% of the distance was traversed before additional visual feedback was obtained. Feedback obtained on that second look was often sufficient to allow subjects to walk very accurately the remaining distance to the target. As was expected, performance at the 2 m target was often accurate with only

one sample of the target. It should also be noted that there was no evidence that sampling occurred after a critical time had elapsed. These data support the two-stage model of target-directed locomotion proposed above. On the first stage of a walk, subjects walked the approximate distance to the target, but undershot it. On the second stage, subjects used visual feedback to make their performance accurate relative to the target.

As I indicated earlier, the nature of visual control during locomotion is poorly understood. Issues that need to be addressed include (1) how often targets are sampled and (2) how that sampling changes with changing environmental conditions. It seems reasonable that complex environments and high speeds would require increased sampling rates. For this reason alone, a simple dichotomy between continuous and discontinuous visual feedback is self-limiting.

Thomson's short-term memory -- other problems

Another consequence of Thomson's 8 s transient short-term memory is the requirement of reasonably precise time keeping. An accurate time counter would have to be available in order to maintain ongoing behavior by switching control of locomotion from the image of the target to the target itself at the critical time. If a timer is not available one would have to be content with not being able to predict the availability of the image. This uncertainty might lead one to switch control back to the target before 8 s had elapsed. If in the meantime the target had gone out of view, then performance would suddenly become very inaccurate. Thus, if time keeping were not precise, performance would break down over a range of times and not

abruptly at 8 s as Thomson (1980, 1983) reported. Of course, much of this is conjecture, since there is no experimental evidence to support precise time keeping abilities. Nevertheless this and the preceeding exercises in logic illustrate just how much additional conceptual baggage is required by Thomson's deceptively simple short-term memory hypothesis.

There is another problem as well. Since sensory biases and errors are the rule rather than the exception (Poulton, 1975), the veridical nature of Thomson's short-term memory must also be questioned. There is no evidence either in the sensory or the motor literature that information about target locations is coded and/or reproduced in an undistorted manner. Studies examining the effect of target distance on perceptual accuracy indicate that errors should increase with increased target distance. Even if Thomson's subjects were using a mental image of the environment, there is no evidence that such mental images preserve spatial information in a precise way. Although information about the relative locations of objects in the environment may well be preserved in mental images of the environment (Corballis, 1982), little is known about how information about the actual distance between objects is preserved. Moreover, there is evidence to suggest that mental images are also affected by sensory and cognitive biases (Kosslyn, 1985). I contend that the accuracy of any short-term memory or mental image of a target location should be limited by errors and biases inherent in the perceptual system.

Is accurate short-term memory needed to support divided attention?

Since no support was found for the highly accurate transient short-term memory that Thomson (1980, 1983) proposed, what mechanism accounts for the ability of animals to control their behavior with respect to a number of different targets at the same time? An alternative explanation of the behaving animal's ability to process visual information about a variety of different environmental factors simultaneously can be found in work showing that there are a number of functionally and anatomically independent, but interactive visuomotor systems (for example, Goodale & Milner, 1982; Ingle, 1982). Thus information about prey and obstacles in the environment would be obtained continuously and in parallel. (For a more detailed discussion of these parallel systems see Goodale, in press.)

Target-directed locomotion and environmental demands

Since action takes place in the environment, theories regarding the control of locomotion must take into account how changes in the environment change behavior (see Gibson, 1979). If vision were to be suddenly occluded near a cliff, the need for accuracy would depend on just how close one was to the edge. At 3 m, every step would count, but at 9 m, it would not matter whether the edge was considered a step or two nearer or farther away than it actually was. However, it would be adaptive if errors, based on information available before vision was occluded, would lead one to stop walking before the edge was reached rather than as one was falling into the abyss (see Fisk & Goodale, 1985 for a similar point about constant errors during reaching). Consequently, errors of underestimation, similar to those reported

here, may have survival value in some situations.

There are situations where errors of underestimation would not be advantageous. In those instances, a different type of error would be predicted. For example, errors of underestimation would be disadvantageous when jumping an obstacle like a stream. Generally, one does not attempt to do this from distances of more than 3 m where performance accuracy has been shown to be about the same as it is with full visual feedback. In fact, variable errors are small and constant errors tend either to overestimate the distance to the target or to vary around the target. Intuition and introspection would predict that a 'better safe than sorry' strategy would typify performance on such a task -- subjects would probably overjump. These overjumps would be predicted to vary around a target position that would make failures (errors of underestimation) infrequent. Conversely, targets near a wall or other large obstacle should be associated with enhanced errors of underestimation. Different aspects of the environment should affect behavior in a way that minimizes failures and maximizes successes. Failures would include falling off cliffs, walking into obstacles, and jumping into streams (unless a swim was the intention)!

The environment -- near-space and far- space

Several investigators have suggested that performance with respect to near targets is controlled by a different mechanism from the one that controls performance with respect to more distant targets (Grüsser, 1982; Thomson, 1980, 1983). Some of the evidence, presented here, supports a distinction between near- and far-space, but other data do not. A separation between performance at the 3 m and 9 m

target distances is supported by the following: (1) blind walks up to 3 m away were as accurate as those with full visual feedback while walks beyond 3 m were not; (2) variable errors at the 3 m target were not correlated with variable errors at the 9 m target; and (3) errors at the 3 m target on a perceptual task correlated with locomotor performance and spatial ability in a much stronger way than errors at the 9 m target did. These data might be taken as an indication of superior coding of targets up to 3 m. They might even suggest that performance at this distance was governed by a different mechanism than targets beyond 3 m. The suggestion that performance for a near target is controlled by a different mechanism than the one that controls performance for a far target is weakened by other evidence, however. Although walks without visual feedback to the 3 m target were not significantly different from walks with visual feedback, a critical examination of the data indicates that differences may well have been found with a sufficiently large number of observations. Additionally, the effects of both delay and subject rotation occurred at all target distances, including 3 m. The very large errors caused by the rotation task seems to indicate that the 'representation' of near target locations was not a motor program (Thomson, 1980, 1983) which could simply be run off. The present data suggest that information about near targets is stored in short-term memory in the same way that information about more distant targets is.

Accuracy of target-directed locomotion

From the present investigations, it can be concluded that the accuracy of target-directed locomotion depends on the distance to the

target, the availability of visual feedback, and the direction the subject walks relative to the target. Basic psychophysical relations exist between sensory magnitude and response biases. Absolute and variable errors increase in a linear fashion with increased target distance. Constant errors, on the other hand, often exhibit 'range effects'. The results of the present experiments support the suggestion that constant errors relate to perceptual processes while variable errors are more likely to be influenced by factors that increase the memory load (Laabs, 1979; Laabs & Simmons, 1980).

For walks toward a target, accuracy depends on the amount of visual feedback available to the subject. Walks with reduced or no visual feedback are less accucate than those with full visual feedback. Being able to see the area around the target, in the absence of the target itself, leads to better performance than is possible if one walks with their eyes closed. I would suggest, therefore, that once a target has gone out of view, vision is used to choose a 'new' target. If visual context does not contribute to the choice of the substitute target location, a dissociation between errors may be found. Thus, a subject might be very mistaken about the location of a target (large constant errors), but he/she can choose that wrong location very consistently (small variable errors). Accuracy in choosing the new target will be enhanced or reduced by the nature of the contextual information. The contribution of specific cues in the environment to the choice of a substitute target has not been investigated. A new target may be provided by cues in the area around the original target or it may be provided by other cues in the environment that are more

distant from the original target.

Mental Rotation of the environment

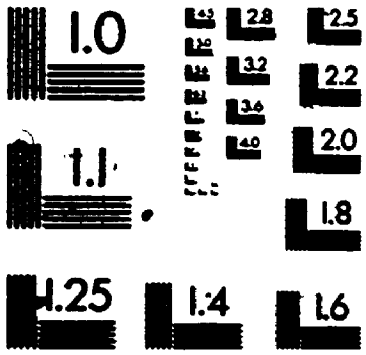
In the present study, substantial errors of overestimation were found when subjects walked in the opposite direction to the target. Why errors of overestimation occurred is a matter of speculation. It may well be coincidental that these constant errors were about the size of an average pace or an arm's length. On the other hand, this finding may indicate that an area, perhaps, what Grüsser (1982a, 1982b) termed 'grasping space' or what could be called 'operational space' remains with the subject during rotation. If this constant space is added onto the new environment, then errors of overestimation will result.

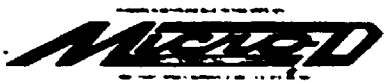
The relation between the type of mental transposition required when subjects turned and walked in the opposite direction to the target and mental rotation tested by many written tests of spatial ability has not been investigated. Studies of mental rotation in environmental settings have focussed on the ability to maintain one's orientation relative to a particular spatial layout, but not whether such rotations introduce systematic errors in visuomotor performance. Corballis (1982) states that "With respect to mental rotation, one can .... contrast mental rotation of the environment with mental rotation of the self" (p. 178). Imagining a scene has been reported to be easier if the subject stands in the appropriate location in the environment than if he/she stands elsewhere (Pick & Reiser, 1982). Evidence from studies with children also indicate that when one is required to view the environment from a different perspective, it is more difficult to rotate a room than it is to transpose oneself to a new location in the

room (Hardwick, McIntyre, & Pick, 1976; Huttenlocher & Presson, 1979).

Apparently, there are differences between situations in which one views the environment from an objective perspective and situations in where subjective perspective is necessary. The ability to take an objective perspective or bird's eye view could be considered a requirement in the formation of spatial representations such as maps, drawings, and models. In the present experiments, when a subject turned and walked in the opposite direction to the target, a subjective perspective was required. This subjective perspective was associated with a distortion in the remembered location of the target. The present study suggests that we may not be able either to move a target to a new location that is behind us or we may not rotate the whole environment without losing a significant amount of accuracy. It is not clear whether subjects attempted to move the target and remap it onto the new environment or whether they attempted to rotate the original environment including the target and use it to guide their locomotion. It should be noted that spontaneous strategies like the pace-estimation strategy, reported in chapter 1, should be able to avoid biases created by a rotation of space and/or the transposition of an object into a new space.

Further investigation is necessary to determine whether visual space which includes the observer/actor is the same as representational space, which some investigators consider to be a "cycloramic 360-degree field" (Attneave & Farrar, 1977, p. 561). Attneave and his colleagues found that subjects were able to report the location of objects behind them, suggesting that the layout of the environment was preserved when





the subject changed his/her orientation. As was suggested above, one distinction between action space and representational space may be the difference between a requirement to view the environment from an objective perspective as compared to a requirement to view it from a subjective point of view.

Spatial ability and spatial behavior

Performance on written tests of spatial ability did not relate to performance on a target-directed locomotion task. Thus, an assumption that locomotor performance under conditions of reduced visual feedback would be related to spatial ability was not supported. However, convincing evidence that performance on a perceptual task related to spatial ability was found, even though a relatively small number of subjects was used. The findings are highly suggestive of a strong relationship between perceptual ability and spatial ability.

Aside from the assumption that locomotion with eyes closed was a 'spatial ability', other evidence indicated that a similar ability might be tapped by the locomotor task and by standard tests of spatial ability. The fact that consistent sex differences were found on the locomotion task and consistent sex differences are reported on written tests of spatial ability led to a prediction that there would be a relation between these two variables. This position was not supported. The present findings suggest that males and females may well differ in their ability to performance a number of independent visuomotor, spatial, and visuomotor-spatial tasks. A critical degree of independence may result from the specific demands of different tasks. At the same time, overlap may result from commonalties between the

perceptual, motor, and cognitive processes that are required to perform such tasks.

Summary

This thesis has shown that the apparently simple and uninteresting problem of how we find our way to targets in the immediate environment (small-scale space in the lexicon of the cognitive psychologist) is neither simple nor uninteresting. Accurate locomotor performance depends on a number of complex variables. Although the studies presented here just begin to examine those variables and their interactions, the contribution of cognitive and perceptual processs to locomotor performance appears to depend on the environment in which the subject is required to walk. Some of the findings supported my intuitions about the phenomenon and were consistent with data in both the perceptual and cognitive literature. First, the further one must walk when visual feedback is limited, the worse one performs. Second, the mental representation one has of the immediate environment reflects the inaccuracy in the initial perception of the target location, and this mental representation deteriorates very little even over a period as long as 30 s. Other findings were quite surprising and pose a number of questions, as yet unanswered, about the nature of mental representations of the environment. For example, the space in front of us appears to be represented in a very different way from the space behind us.

At present, we have no adequate theory to account for the way in we which use visual feedback to control locomotion. I have suggested, just as others have, that changes in the environment should affect

locomotor performance in a way that is adaptive to survival, allowing the organism to survive and reproduce. But surviving through successful locomotion can mean a number of different things. It can mean not falling off a cliff or into a stream; it can mean catching prey or avoiding a predator; and it can mean pursuing a mate and chasing after young. Thus, any theory about the role of visual feedback should be able to deal with the control of locomotion in all of these situations. In the present experiments, I used a very simple task involving a single, stationary target. It would be very interesting to determine if the relations that were demonstrated here generalize to a more complex environment in which subjects, for example, were asked to pursue a target while at the same time negotiating a number of obstacles. Until we are prepared to study locomotion in rich and complex environments, we will fall well short of a complete understanding of how visual feedback and visuospatial memory control this behavior.

The data presented in this thesis suggests that one needs to be able to see a target in order to reach it accurately. Nevertheless, visuospatial memory of target locations can be used to produce adequate locomotor performance when one does not have full visual feedback. Thus, the data seem to indicate that humans are able to guide their locomotion to stationary targets in an uncluttered environment with only limited visual feedback.

APPENDIX A

Table A-1
Partial correlations between errors at the near target on the perceptual task and errors on the locomotion task controlling for the effects of the Money road map test

Locomotor errors	Perceptual errors at 3 m		
	Constant	Absolute	Variable
Constant			
3 m	.4665*	.4740*	.5312*
9 m	.4083#	.2451	.5882**
all	.4548*	.2429	.6462**
Absolute			
3 m	.4032#	.4990*	.6304**
9 m	.3564#	.3130	.4420#
all	.4476#	.3274	.5703*
Variable			
3 m	.3297	.2097	.4767*
9 m	.3302	-.2218	.1916
all	.4172#	-.1149	.2927

Note.
Two-tailed tests of significance: # $p \leq .10$, *$p \leq .05$, *$p \leq .01$.
$df = 18$.

Table A-2
Partial correlations between errors at the near target on the perceptual task and errors on the locomotion task controlling for the effects of the Money road map, Paper folding, and Cube comparisons tests

Locomotor errors	Perceptual errors at 3 m		
	Constant	Absolute	Variable
Constant			
3 m	.4558#	.4805*	.5369*
9 m	.5062*	.2297	.6642**
all	.5442*	.2557	.6299**
Absolute			
3 m	.4607#	.4741#	.6126**
9 m	.3290	.2964	.4233#
all	.4597#	.2983	.5460*
Variable			
3 m	.4286#	.2148	.5107*
9 m	.3330	-.1987	.2324
all	.3748#	-.0925	.3381

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, **$p \leq .010$.
$df = 15$.

APPENDIX B

Table B-1
Correlations between subject variables

Variable	Vision	Pace	Sports	Height
Sex[a]	-.1699	.3026*	.4443**	.6465**
Vision[b]	-	-.2720*	-.0458	-.2176*
Pace[c]		-	-.2434	.3519**
Sports[b]			-	.2684*
Height[d]				-

Note.
Two-tailed tests of significance: *$p \leq .05$,
**$p \leq .010$.
a $n = 78$.
b $n = 58$.
c $n = 70$.
d $n = 71$.

Table B-2
Correlations between z-scores of locomotor errors and subject variables for the females

	Measures			
	Vision[a]	Pace[b]	Sports[a]	Height[c]
Error				
Constant				
Mean	.0788	-.0940	.0661	.0400
3 m	-.0600	-.1003	.0747	-.0998
9 m	.0590	.0380	.0294	.0172
Variable				
Mean	.0272	.0294	.0238	-.0674
3 m	.0262	-.0332	-.1430	-.2762#
9 m	-.0921	.1967	-.1565	-.1271
Absolute				
Mean	.2546	.0062	-.0311	-.4649**
3 m	.1959	-.0607	-.0647	-.2947#
9 m	.1589	.0649	-.0579	-.3405*

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, **$p \leq .010$.
a $n = 28$.
b $n = 32$.
c $n = 33$.

Table B-3
Correlations between z-scores of locomotor errors and subject variables for the males

	Measures			
	Vision[a]	Pace[b]	Sports[a]	Height[b]
Error				
Constant				
Mean	-.0402	.2117	.1938	-.2881#
3 m	-.0210	.0516	.1000	-.4474***
9 m	-.3481#	.3304*	.1735	-.0845
Variable				
Mean	.0605	-.0225	.0527	.0887
3 m	-.3070#	.0454	-.0399	.0799
9 m	.2425	-.0469	-.1448	-.1212
Absolute				
Mean	.0113	-.0906	-.1179	.1661
3 m	-.0376	-.0667	.0354	.3433*
9 m	.1866	-.2842#	-.2389	.0438

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, ***$p \leq .005$.
a $n = 30$.
b $n = 38$.

Table B-4
Walking speed compared with subject variables

Variable	Walking speed		
	Mean	3 m	9 m
Sex[a]	.1394	.0281	.0919
Vision[b]	-.2942*	-.2464#	-.2710*
Pace[c]	.3391***	.3391***	.4462***
Sports[b]	-.2438#	-.3124*	-.3057*
Height[d]	.0416	-.0524	.0248

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, ***$p \leq .005$.
a $n = 78$.
b $n = 58$.
c $n = 70$.
d $n = 71$.

Table B-5
Walking speed compared with subject variables for females and males

Variable	Walking speed		
	Mean Speed	3 m Speed	9 m Speed
	Females		
Vision[a]	-.2871#	-.3778*	-.3342#
Pace[b]	.1453	.1722	.2668#
Sports[a]	-.1626	-.1960	-.1588
Height[c]	-.0146	.0709	.0275
	Males		
Vision[d]	-.3040#	-.1976	-.2541
Pace[e]	.5257***	.4867***	.5933***
Sports[d]	-.3416#	-.3515#	-.3799*
Height[e]	.0033	-.0944	.0238

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, ***$p \leq .005$.
a $n = 28$.
b $n = 32$.
d $n = 33$.
d $n = 30$.
e $n = 38$.

Table B-6
Walking speed related with locomotor errors for females

	Walking speed		
	Mean	3 m	9 m
Error			
Constant			
Mean	.3777*	.3360*	.4520***
3 m	.3751*	.3767*	.3336*
9 m	.3142#	.2324	.4450**
Variable			
Mean	-.0489	-.1095	-.0604
3 m	.1451	.0322	.1822
9 m	-.2791#	-.3494*	-.2626#
Absolute			
Mean	-.0746	-.2062	-.0790
3 m	.2009	.1177	.2199
9 m	-.0191	-.1670	-.0975

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, **$p \leq .010$, ***$p \leq .005$.
$n = 38$.

Table B-7
Walking speed related with locomotor errors for males

	Walking speed		
	Mean speed	3 m speed	9 m speed
Error			
Constant			
Mean	.0057	.1647	.2150
3 m	.0170	.2823#	.1916
9 m	.1460	.2513#	.3820*
Variable			
Mean	.1119	-.0076	-.0486
3 m	.1790	.2126	.1345
9 m	.0299	.0153	-.0770
Absolute			
Mean	-.1449	-.3700*	-.3899*
3 m	-.0054	-.1897	-.0982
9 m	-.1338	-.2723#	-.3128*

Note.
Two-tailed tests of significance: #$p \leq .10$,
*$p \leq .05$.
$n = 40$.

Table B-8
Correlations between locomotor errors for females and males

Error	Interdistance correlations		
	Mean x 3 m	Mean x 9 m	3 m x 9 m
	Females[a]		
Constant	.7048***	.8710***	.6065***
Variable	.2572#	.5861***	.2497#
Absolute	.5870***	.8788***	.5412***
	Males[b]		
Constant	.5590***	.7492***	.3823*
Variable	.2281	.6958***	.1824
Absolute	.3014#	.5775***	.0696

Note.
Two-tailed tests of significance: #$p \leq .10$, *$p \leq .05$, ***$p \leq .005$.
a $n = 38$.
b $n = 40$.

Table B-9
Absolute locomotor errors for Experiments 1-6

	Distance							
	3 m	6 m	9 m	12 m	15 m	18 m	21 m	Grand (mean)
Experiment								
1								
males:	.14	.21	.36	.50	.56	.74	.71	.46
females:	.19	.41	.56	.89	1.07	1.15	1.19	.78
2								
males:	.30	.67	.97	1.30	1.50			.95
females:	.42	.86	1.28	1.65	2.16			1.27
3								
males	.19	.36	.58	.86				.50
females:	.24	.60	.99	1.58				.85
4								
males:	.38	.41	.49	.68				.49
females:	.43	.50	1.13	1.44				.86

	1 m	3 m	5 m	7 m	9 m	11 m	Grand (mean)
5							
males:	.24	.40	.47	.57	.69	.75	.54
females:	.19	.38	.63	1.03	1.19	1.11	.75

	3 m	6 m	9 m	12 m	Grand (mean)
6					
males:	.45	.72	.88	1.10	.79
females:	.65	.88	1.04	1.13	.93

Table B-10
Analyses of variance for the effect of sex on absolute errors for Experiments 1 - 6

Experiment 1:
Sex: $F(1,18) = 9.06$, $p = .0075$
Sex by distance: $F(6,108) = 2.29$, $p = .041$

Experiment 2:
Sex: $F(1,18) = 1.92$, $p = .183$

Experiment 3:
Sex: $F(1,12) = 3.30$, $p = .094$ (trend)
Sex by distance $F(3,36) = 2.58$, $p = .069$ (trend)

Experiment 4:
Sex: $F(1,10) = 17.08$, $p = .002$
Sex by distance: $F(3,30) = 9.53$, $p = .00014$

Experiment 5:
Sex $F(1,8) = 1.48$, $p = .258$
Sex by distance: $F(5,40) = 2.66$, $p = .036$

Experiment 6:
Sex: $F(1,7) = 4.80$, $p = .065$ (trend)

Table B-11
Constant locomotor errors for Experiments 1-6

	Distance							
	3 m	6 m	9 m	12 m	15 m	18 m	21 m	Grand (mean)
Experiment								
1								
males:	-.05	-.11	-.42	-.60	-.51	.11	-1.32	-.12
females:	.03	-.25	-.86	-1.44	-1.74	-1.45	-1.24	-.48
2								
males:	-.02	-.20	-.55	-.32	.07			-.19
females:	.17	-.35	-.10	-.27	.07			-.03
3								
males	.04	-.14	-.22	-.38				.17
females:	-.11	-.53	-.80	-1.45				-.78
4								
males:	.29	.14	-.19	-.15				.03
females:	.31	-.21	-.37	-.95				-.28

	1 m	3 m	5 m	7 m	9 m	11 m	Grand (mean)
5 (Eyes closed walks only)							
males:	.39	.35	.27	.27	.24	.49	.23
females:	-.02	-.01	-.36	-.61	-.92	-.75	-.46

	3 m	6 m	9 m	12 m	Grand (mean)
6 (Eyes closed walks toward the target only)					
males:	.17	-.11	-.34	-.27	-.15
females:	.27	.10	-.44	-.15	-.11

Table 8-12
Analyses of variance for the effect of sex on constant errors for Experiments 1 - 6

Experiment 1:
Sex: $F(1,18) = 4.02$, $p = .060$
Sex by distance: $F(6,108) = 2.83$, $p = .01$

Experiment 2:
Sex: $F(1,18) = .119$, $p = .735$
Sex by distance: $F(2,36) = 2.45$, $p = .101$

Experiment 3:
Sex: $F(1,12) = 4.34$, $p = .059$
Sex by distance: $F(3,36) = 3.42$, $p = .027$

Experiment 4:
Sex: $F(1,10) = 1.67$, $p = .226$
Sex by distance: $F(3,30) = 2.86$, $p = .053$

Experiment 5 (Eyes closed walks only):
Sex $F(1,8) = 3.52$, $p = .0973$
Sex by distance: $F(5,40) = 2.35$, $p = .06$

Experiment 6 (Eyes closed walks toward the target only):
Sex: $F(1,7) = .022$, $p = .891$
Sex by distance: $F(3,21) = .140$, $p = .94$

REFERENCES

Acredolo, L.P. (1981). Small- and large-scale spatial concepts in infancy and childhood. In L.S. Liben, A.H. Patterson, & N. Newcombe (Eds.), Spatial representation and behavior across the life span (pp. 63-79). New York: Academic Press.

Adams, J.A. & Dijsktra, S. (1966). Short-term memory for motor responses. Journal of Experimental Psychology, 71, 314-318.

Attneave, F. & Farrar, P. (1977). The visual world behind the head. American Journal of Psychology, 90, 549-563.

Baird, J.C. (1970). Psychophysical analysis of visual space. Oxford: Pergamon Press.

Berry, J.W. (1966). Temne and Eskimo perceptual skills. International Journal of Psychology, 1, 207-229.

Campione, J.C., Brown, A.L., & Bryant, N.R. (1985). Individual differences in learning and memory. In R.J. Sternberg (Ed.), Human abilities: An information-processing approach (pp. 103-126). New York: W.H. Freeman & Co.

Corballis, M.C. (1982). Mental rotation: Anatomy of a paradigm. In M. Potegal (Ed.), Spatial abilities: Development and physiological foundations (pp. 173-198). New York: Academic Press, Inc.

Corlett, J.T., Patla, A.E., & Williams, J.G. (1985). Locomotor estimation after visual scanning by children and adults. Perception, 14, 257-263.

Corlett, J.T., & Patla, A.E. (1986). Some effects of upward, downward, and level visual scanning and locomotion on distance estimation accuracy. Journal of Human Movement Studies, 1-11.

Dale, H.C.A. (1973). Short-term memory for visual information. British Journal of Psychology, 64, 1-8.

Down, R.M. & Siegel, A.W. (1981). On mapping researchers mapping children mapping space. In L.S. Liben, A.H. Patterson, & N. Newcombe (Eds.), Spatial representation and behavior across the life span (pp. 237-248). New York: Academic Press.

Droogleever Fortuyn, J. (1982). On the organization of spatial behavior. Human Neurobiology, 1, 145-151.

Elliott, D. (1986). Continuous visual information may be important after all: A failure to replicate Thomson. Journal of Experimental Psychology: Human Perception and Performance, 12, 388-391.

Fisk, J.D. & Goodale, M.A. (1985). The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. Experimental Brain Research, 60, 159-178.

Fitch, H.L. Tuller, B. & Turvey, M.T. (1982). The Bernstein perspective: III. Tuning of coordinative structures with special reference to perception. In J.A. Kelso (Ed.), Human motor behavior: An introduction (pp. 253-281). Hillsdale NJ: Lawrence Erlbaum Associates, Inc.

Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47, 318-391.

French, J.W., Ekstrom, R.B., & Price, L.A. (1963). Manual for Kit of References Tests for Cognitive Factors. Princeton, NJ: Educational Testing Service.

Gibson, E.J. & Bergman, R. (1954). The effect of training on absolute estimation of distance over the ground. Journal of Experimental Psychology, 48, 473-482.

Gibson, J.J. (1958). Visually controlled locomotion and visual orientation in animals. British Journal of Psychology, 49, 182-194.

Gibson, J.J. (1966). The senses considered as a perceptual system. Boston: Houghton Mifflin.

Gibson, J.J. (1979). The ecological approach to visual perception. Boston: Houghton Mifflin Co.

Gilinsky, A. (1951). Perceived size and distance in visual space. Psychological Review, 58, 460-482.

Glanzer, M. & Clark, W.H. (1962). Accuracy of perceptual recall: An analysis of organization. Journal of Verbal Learning and Verbal Behavior, 1, 289-299.

Goodale, M.A. (1983a). Neural mechanisms of visual orientation in rodents: Targets versus places. In M. Jeannerod & A. Hein (Eds.), Spatially oriented behavior (pp. 35-57). New York: Springer-Verlag.

Goodale, M.A. (1983b). Vision as a sensorimotor system. In T.E. Robinson (Ed.), Behavioral Approaches to Brain Research (pp. 41-61). Oxford University Press.

Goodale, M.A. (in press). Modularity in visuomotor control: From input to output. Z. Pylyshyn (Ed.), Computational Processes in Human vision: An interdisciplinary perspective, Norwood NJ: Ablex Publishing Corp.

Goodale, M.A., Pelisson, D., & Prablanc, C. (1986). Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. Nature, 320, 748-750.

Grüsser, O.-J. (1982a). Space perception and the gazemotor system. Human Neurobiology, 1, 73-76.

Grüsser, O.-J. (1982b). Multimodal structure of the extrapersonal space. In M. Jeannerod & A. Hein (Eds.), Spatially oriented behavior (pp. 227-252). New York: Springer-Verlag.

Guildford, J.P. & Zimmerman, W.S. (1953). Guildford-Zimmerman Aptitude Survey. Orange, Calif: Sheridan Psychological Services.

Hamlyn, D.W. (1977). The concept of information in Gibson's theory of perception. Journal for the Theory of Social Behavior, 7, 5-16.

Hardwick, D.A., McIntyre, C.W., & Pick, H. (1976). Content of manipulation of cognitive maps in children and adults. Monographs of the Society for Research in Child Development, 41 (3, Serial No. 166).

Harris, L.J. (1978) Sex differences in spatial ability: Possible environmental, genetic, and neurological factors. In M. Kinsborne (Ed.), Asymmetrical function of the brain (pp. 405-522). New York: Cambridge University Press.

Harris, L.J. (1981). Sex related variations in spatial skill. In L.S. Liben, A.H. Patterson, & N. Newcombe (Eds.), Spatial

representation and behavior across the life span (pp. 83-117). New York: Academic Press.

Hart, R.A. & Moore, G.T. (1973). The development of spatial cognition: A review. In R. M. Downs & D. Stea (Eds.), Image and environment: Cognitive mapping and spatial behavior. Chicago: Aldine.

Harway, N.I. (1963). Judgment of distance in children and adults. Journal of Experimental Psychology, 65, 385-390.

Heil, J. (1981). Gibson's sins of omission. Journal for the Theory of Social Behavior, 11, 307-311.

Holding, D.H. (1968). Accuracy of delayed aiming responses. Psychonomic Society, 12, 125-126.

Hollingworth, H.L. (1909). The inaccuracy of movement with special reference to constant errors. Archives of Psychology, 13, 1-87.

Howarth, C.I. & Beggs, W.D.A. (1981). Discrete movements. In D. Holding (Ed.), Human skills (pp. 92-117). New York: John Wiley & Sons Ltd.

Huttenlocher, J. & Presson, C.C. (1979). The coding and transformation of spatial information. Cognitive Psychology, 11, 375-394.

Ingle, D.J. (1982). Organization of visuomotor behaviors in vertebrates. In D.J. Ingle, M.A. Goodale & R. J. W. Mansfield (Eds.), Analysis of visual behavior (pp. 67-109). Cambridge, MA: MIT Press.

Jansson, G. (1983). Tactile guidance of movement. International Journal of Neuroscience, 19, 37-46.

Jardine, R. and Martin, N.G. (1983). Spatial ability and throwing accuracy. Behavior Genetics, 13, 331-340.

Johansson, G. (1977). Studies on visual perception of locomotion. Perception, 6, 365-376.

Keele, S.W. (1968). Movement control in skilled motor performance. Psychological Bulletin, 70, 387-403.

Kelso, J.A. (1982). The process approach to understanding human motor behavior: An introduction. In J.A. Kelso (Ed.), Human motor behavior (pp. 3-20). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Kirk, R.E. (1968). Experimental design: Procedures for the behavioral sciences. Belmont, CA: Brook/Cole Pub. Co.

Kolakowski, D. & Malina, R.M. (1974). Spatial ability, throwing accuracy, and man's hunting heritage. Nature, 251, 410-412.

Kosslyn, S.M. (1985). Mental imagery ability. In R.J. Sternberg (Ed.), Human abilities: An information-processing approach (pp. 151-172). New York: W.H. Freeman & Co.

Kunnapas, T.M. (1960). Scales for subjective distance. Scandinavian Journal of Psychology, 1, 187-192.

Laabs, G.J. (1979). On perceptual processing in motor memory. In C.H. Nadeau, W. R. Halliwell, K.M. Newell, & G.C. Roberts (Eds.), Psychology of motor behavior and sport - 1979. (pp. 432-444). Champaign, IL: Human Kinetics Pub.

Laabs, G.J. & Simmons, R.W. (1981). Motor memory. In D. Holding (Ed.), Human skills (pp. 119-151). New York: John Wiley & Sons Ltd.

Lee, D.N. (1974). Visual information during locomotion. In R.B. MacLeod and H.L. Pick (Eds.), Perception: Essays in honor of James J. Gibson. Ithaca & London: Cornell University Press.

Lee, D.N. (1976). A theory of visual control of braking based on information about time-to-collision. Perception, 5, 437-459.

Lee, D.N. (1978). The functions of vision. In H.L. Pick and E. Saltzman (Eds.), Modes of perceiving and processing information. Hillsdale, NJ: Erlbaum Press.

Lee, D.N & Lishman, J.R. (1977). Visual control of locomotion. Scandinavian Journal of Psychology, 18, 224-230.

Lee, D.N. & Thomson, J.A. (1982). Vision in action: The control of locomotion. In D.J. Ingle, M.A. Goodale & R. J. W. Mansfield (Eds.), Analysis of visual behavior (pp. 411-433). Cambridge, MA: MIT Press.

Liben, L.S. (1981). Spatial representation and behavior: Multiple perspectives. In L.S. Liben, A.H. Patterson, & N. Newcombe (Eds.), Spatial representation and behavior across the life span (pp. 3-32). New York: Academic Press.

Liben, L.S., Patterson, A.H., & Newcombe, N. (1981). Spatial representation and behavior across the life span. New York: Academic Press.

Lindberg, E. & Garling, T. (1981a). Acquisition of locational information about reference points during blindfolded and sighted locomotion: Effects of a concurrent task and locomotional paths. Scandinavian Journal of Psychology, 22, 101-108.

Lindberg, E. & Garling, T. (1981b). Acquisition of locational information about reference points during locomotion with and without a concurrent task: Effects of number of reference points. Scandinavian Journal of Psychology, 22, 109-115.

Lindberg, E. & Garling, T. (1983). Acquisition of locational information about reference points during locomotion: The role of central processing. Scandinavian Journal of Psychology, 23, 207-218.

Lishman, J.R. & Lee, D.N. (1973). The autonomy of visual kinesthesis. Perception, 2, 287-294.

Llewellyn, K.R. (1971). Visual guidance of locomotion. Journal of Experimental Psychology, 91, 245-291.

McGee, M.G. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. Psychological Bulletin, 86, 889-918.

Menzel, E.W., Premack, D., & Woodruff, G. (1978). Map reading in chimpanzees. Folia Primatologica, 29, 241-249.

Michaels, C.F. & Carello, C. (1981). Direct Perception. Englewood Cliffs, NJ: Prentice-Hall.

Money, J., Alexander, D., & Walker, H.T. Jr. (1965). A standardized test of direction sense. Baltimore, MD: Johns Hopkins University Press.

Neisser, U. (1977). Gibson's ecological optics: Consequences of a different stimulus description. Journal for the Theory of Social Behavior, 7, 17-28.

Newcombe, N. (1981). Spatial representation and behavior: Retrospective and prospective. In L.S. Liben, A.H. Patterson, & N. Newcombe (Eds.), Spatial representation and behavior across the life span (pp. 373-397). New York: Academic Press.

O'Keefe, J. & Nadel, L. (1978). The hippocampus as a cognitive map. Oxford: Oxford University Press.

Olton, D.S. (1978). Characteristics of spatial memory. In S.H. Hulse, H.F. Fowler, and W.K. Honig (Eds.), Cognitive processes in animal behavior (pp. 341-373). Hillsdale, NJ: Erlbaum Associate.

Peterson, L.R. & Peterson, J. (1959). Short-term retention of individual verbal items. Journal of Experimental Psychology, 58, 193-198.

Piaget, J. & Inhelder, B. (1956). The childs concept of space. London: Routledge & Kegan Paul.

Pick, H.L. & Acredolo, L.P. (1983). Spatial orientation: Theory, research, and application. New York: Plenum Press.

Pick, H.L. & Rieser, J.J. (1982). Children's cognitive mapping. In M. Potegal (Ed.), Spatial abilities: Development and physiological foundations (pp. 107-128). New York: Academic Press, Inc.

Posner, M.I. (1967). Characteristics of visual and kinesthetic memory coded. Journal of Experimental Psychology, 75, 103-107.

Poulton, E.C. (1975). Range effects in experiments on people. American Journal of Psychology, 88, 3-32.

Poulton, E.C. (1979). Models for biases in judging sensory magnitude. Psychological Bulletin, 86, 777-803.

Regen, D. & Beverley, K.I. (1979). Visually guided locomotion: Psychophysical evidence for a neural mechanism sensitive to flow patterns. Science, 205, 311-313.

Sadalla, E.K. & Magel, S.G. (1980). The perception of traversed distance. Environment and Behavior, 12, 65-79.

Sandström, C.I. (1951). Orientation in the present space. Stockholm: Almqvist & Wiksell.

Scarr, S. & Carter-Saltzman, L. (1983). Genetics and intelligence. In R. J. Sternberg (Ed.), Handbook of human intelligence (pp. 792-896). New York: Cambridge University Press.

Schiff, W. & Detwiler, M.L. (1979). Information used in judging impending collision. Perception, 8, 647-658.

Schutz, R.W. & Roy, E.A. (1973). Absolute error: the devil in disguise. Journal of Motor Behavior, 5, 141-153.

Searle, L.V. & Taylor, F.V. (1948). Studies of tracking behavior. I. Rate and time characteristics of simple corrective movements. Journal of Experimental Psychology, 38, 615-631.

Skavenski A.A. & Steinman, R.M. (1970). Control of eye position in the dark. Vision Research, 10, 193-203.

Siegel, A.W. (1981). The externalization of cognitive maps by children and adults: In search of ways to ask better questions. In L.S. Liben, A.H. Patterson, & N. Newcombe (Eds.). Spatial representation and behavior across the life span (pp. 167-194). New York: Academic Press.

Slack, C.W. (1953). Some characteristics of the "range effect". Journal of Experimental Psychology, 46(2), 76-80.

Stafford, R.E. (1961). Sex differences in spatial visualization as evidence of sex-linked inheritance. Perceptual and Motor Skills, 13, 428.

Steenhuis, R.E., and Goodale, M.A. (1986). Short-term memory for spatial location: A target-directed locomotion task in normal human subjects. Society for Neuroscience Abstracts, 12, 1447.

Strelow, E.R. (1985). What is needed for a theory of mobility: Direct perception and cognitive maps- lessons from the blind. Psychological Review, 92, 226-248.

Strelow, E.R, & Brabyn J.A. (1981). Use of foreground and background information in visually guided locomotion. Perception, 10, 191-198.

Thomson, J.A. (1980). How do we use visual information to control locomotion? Trends in Neurosciences, 3, 247-250.

Thomson, J.A. (1983). Is continuous visual monitoring necessary in visually guided locomotion. Journal of Experiment Psychology: Human Perception and Performance, 9, 427-443.

Thomson, J.A. Personal Communication, 1985.

Thomson, J.A. (1986). Intermittent versus continuous visual control: A reply to Elliott. Journal of Experimental Psychology: Human Perception and Performance, 12, 392-393.

Tolman, E.C. (1948). Cognitive maps in rats and men. Psychological Review, 55, 189-208.

Turvey, M.T. (1977). Preliminaries to a theory of action with reference to vision. In R. Shaw & J. Bransford (Eds.), Perceiving, acting and knowing: Towards an ecological psychology (pp. 211-265). Hillsdale, NJ: Lawrence Erlbaum Associates.

Vicker, D. (1979). Decision processes in visual perception. New York: Academic Press.

von Hofsten, C. & Lee, D. (1982). Dialogue on perception and action. Human Movement Science, 1, 125-138.

Wagner, M. (1985). The metric of visual space. Perception and Psychophysics, 38, 483-495.

Wallash, H. & O'Leary, A. (1982). Slope of regard as a distance cue. Perception and Psychophysics. 31(2), 145-148.

Walsh, D.A., Krauss, I.K., & Regnier, V.A. (1981). Spatial ability, environmental knowledge, and environmental use: The elderly. In L.S. Liben, A.H. Patterson, & N. Newcombe (Eds.). Spatial representation and behavior across the life span (pp. 321-356). New York: Academic Press.

Watson, N. (1985). Contributions of spatial and timing mechanisms to accuracy on ballistic motor tasks. Unpublished honors thesis, University of Western Ontario, London, Ontario.

Woodworth, R.S. (1899). The accuracy of voluntary movement. Psychological Review, 3, (Monograph Supplement, 2), 1-119.